Effects of Moderate Thermal Environments on Cognitive Performance: A Multidisciplinary Review

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Abstract

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. The present review examines thermal environmental effects on cognitive performance research conducted across multiple disciplines. After differentiating *performance* from *productivity*, we compare the two dominant conceptual models linking thermal stress to performance; (1) the inverted-U concept and (2) the extended-U relationship. The inverted-U specifies a single optimum temperature (or its corresponding subjective thermal sensation) at which performance is maximised. In contrast, the extended-U model posits a broad central plateau across which there is no discernible thermal effect on cognitive performance. This performance plateau is bounded by regions of progressive performance decrements in more extreme thermal conditions. The contradictions between these opposing conceptual models might derive from various confounding factors at play in their underlying research bases. These include, *inter alia*, environment-related, task-related, and performer-related factors, as well as their associated two-way and three-way interaction effects. Methodological discrepancies that might also contribute to the divergence of these conceptual models are evaluated, along with the proposed causal mechanisms underlying the two models. The weight of research evidence reviewed in this paper suggests that the extended-U hypothesis fits the relationship between moderate thermal environments and cognitive performance. **In contrast to the inverted-U relationship, implementation of the extended-U in indoor climate control implies substantial reductions in building energy demand, since it permits the heating and cooling setpoint deadband to expand across the full width of the thermal comfort zone, or even slightly further during emergencies** such as peak demand events on the electricity grid. Use of personal comfort systems can further extend the thermostat setpoint range beyond the comfort zone.

Keywords: thermal environment; thermal stress; cognitive performance; the inverted-U model; the extended-U model

List of Abbreviations: HVAC, heating, ventilation and air conditioning; REHVA, Federation of European Heating, Ventilation and Air Conditioning Associations; ASHRAE, American Society of Heating, Refrigerating, and Air-Conditioning Engineers; GPA, grade point average; TSV, Thermal Sensation Vote; IEQ, Indoor Environmental Quality;; PMV, Predicted Mean Vote; WBGT, wet-bulb globe temperature; ET, effective temperature; LTM, Long-Term Memory; WM, Working Memory; EDT, Environmental Determinism Theory; PCS, Personal Comfort Systems; CLT, cognitive load theory; SWAT, Subjective Workload Assessment Technique; EEG, electroencephalogram; fMRI, functional Magnetic Resonance Imaging; fNIRS, functional Near-Infrared Spectroscopy; ECG, electrocardiography

1. Introduction

1.1 Thermal Environments and Human Performance

The notion of climatic influences over human affairs has a very long history, probably dating back to the Hippocratic writings on "*Airs, Waters and Places*" circa 400 BC ([1], p.4), but its fullest expression had to wait until the so-called climatic determinists of the early Twentieth Century. The most controversial determinist, Ellsworth Huntington, assembled specious *post hoc* evidence in support of his ethnocentric contention that 3 °C outdoors was optimal for mental work under the conditions of housing that prevailed in Connecticut at that time [2]. Simple correlational field studies found that factory outputs in tinplate, steel, and glass industries were generally lower during summers [3,4,5]. In munitions factories, it was observed that accident rates increased as temperature varied from 20 °C [6]. In the coal industry, work rates tapered off as temperatures rose from 17 °C to 32 °C at 80% relative humidity [7]. These early studies were especially concerned with *physical* tasks, their completion rates, associated error rates and safety in traditional industrial settings. However, in recent decades more rigorous investigation into the effect of the thermal environment on human *cognitive performance* has gathered momentum across diverse disciplines. These range from environmental psychology, to physiology, ergonomics, to air conditioning engineering, as well as neuroscience, sports science, education and even linguistics. This field is bifurcated into studies with conditions approaching intolerable thermal stress and those of only moderate thermal load, in or near optimum comfort. Thermal stress is of most relevance in military and industrial settings where the concern is with safety and survival under extreme conditions [8]. Moderate thermal environmental research is predominantly focused on civilians in or near the comfort zone [9,10].

Heat stress is a common risk factor across diverse activities in mining, shearing, farming, manufacturing, firefighting and other emergency activities, outdoor sports, as well as military occupations. The settings for cold stress also include military operations but also include fishing trawler work, emergency disaster work, and winter sports [11]. Severe environmental heat can compromise the cardiovascular system's ability to maintain a constant body temperature due to an accumulation of body heat, resulting in physiological dysfunction, heat exhaustion and, if left unchecked, ultimately death [12,13]. Similarly, severe cold exposure prompts a variety of compensatory physiological responses, but if they are unable to maintain body heat content, a decrement in core temperature ensues, resulting in mental confusion, unconsciousness, and finally death due to heart failure [14,15]. While the physiological responses to environmental heat or cold are well understood, their impact on cognition remains relatively less clear [13,16], particularly for cold exposures [9,17,18,19].

The focus of the present paper is on indoor thermal environments where, depending on outdoor climate, building structure, internal heating/cooling loads, and the active heating and cooling equipment in place, temperatures vary from the high-teens to the low-thirties (°C). These moderate indoor thermal environments are far from the hyper- and hypothermic scenarios described above 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.

1.2 Thermal Environments and Building Energy Use

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 [20] are able to achieve acceptable indoor environments. Secondly, the indoor design temperature range directly impacts energy required by heating, ventilation and air conditioning (HVAC) systems to achieve them [21]. 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 ± 1.5 °C around an invariant optimum temperature could ensure 90% occupant thermal acceptability [22,23]. 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. [24,25]). 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 The Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) and The American Society of Heating, Refrigerating, and Air-

conditioning Engineers (ASHRAE) shifted their justifications for tight indoor temperature control away from occupant *comfort* towards occupant *productivity*. The REHVA Guidebook [26] and ASHRAE Handbook of Fundamentals [27] depict a very narrow indoor temperature range for optimal productivity, which has resulted in significant summer over-cooling and winter over-heating worldwide [28,29,30]. Ideally, HVAC systems should provide *satisfactory* thermal conditions and indoor air quality at the *minimal* expense of energy consumption and negative impact on the environment [31]. In reality buildings accounted for one third of total global final energy use in 2010 [32], much of it related to indoor environmental quality, particularly thermal energy uses [28,29,33,34]. Currently, the building sector is the largest energy consumer worldwide [35] and a typical office building HVAC system accounts for approximately 40% of total-building energy and 70% of base-building energy [36]. In Australia the summer indoor thermal performance specifications of 22.5 ± 1.5 °C embedded in most commercial office tenancy agreements [37] are below the ASHRAE standard-55 summer comfort zone [38]. Such energy intensive over-cooling in commercial buildings is ubiquitous in many developed countries. Despite being widely derided as “the luxurious discomfort of the rich” [30] requiring excessive energy use [39], it is simplistically justified in terms of productivity gains from expensive human resources. Since REHVA and ASHRAE exert a strong influence on air conditioning practices, HVAC-related energy use, and greenhouse gas emissions well beyond their European and North American jurisdictions, it behoves us to critically review the scientific evidence put forward in support of temperature effects on cognitive performance and productivity.

This paper presents a multidisciplinary review of the studies focusing on the effects of moderate thermal environment on cognitive performance. It describes the systematic review methodology in Section 2; three similar concepts (activity, performance and productivity) are differentiated in Section 3; Section 4 introduces two overarching conceptual models linking thermal stress and cognitive performance—the inverted-U model and the extended-U model; Section 5 then reconciles conflicts between these two models by identifying mediating factors, discovering underlying mechanisms behind the two models, and exploring methodological discrepancies leading to divergence of models. Section 6 discusses the practical implications of the two models in terms of indoor environmental control and attendant building energy; Section 7 presents the final conclusions of the review and Section 8 identifies fruitful future research topics.

2. Methodology

2.1 Multidisciplinary approach

The research theme of thermal environment vs. human performance gained rapid popularity probably after the emergence of indoor environmental quality (IEQ) concept [40] and accompanying research questions on IEQ effects on office productivity [41,42,43,44,45,46]. Being one of the most significant IEQ factors in terms of energy costs, indoor thermal environment has received close attention in the research literature. Due to the applied nature of the IEQ field, focus has been on establishing links between physical indoor environmental factors and human responses as an approach to optimizing building management, operation and control [47]. Arithmetic relationships have been proposed by different researchers to quantify the productivity decrement in percentage terms as room temperature (or thermal sensation) deviates from the temperature optimum. These functions have then often been subjected to cost-benefit analyses that trade off the costs of lost productivity from the building’s workforce against the costs of variations in building and building services design, retrofits, and operational facilities’ management practices [46,48,49,50,51,52,53]. However, carried out through specific IEQ disciplinary lens, these studies often lack underlying theories and ignore causal mechanisms. In his wide-ranging survey of the indoor environmental research domain Corsi ([54], p.231) 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 intellectual insularity is clearly evident in cognitive performance research theme in the indoor environmental sciences and engineering (e.g. Seppänen and Fisk [50], Seppänen et al. [52], Kosonen & Tan [55], Jensen et al. [56], Lan and Lian [57], Lan et al. [58], Lan et al. [53]) which have generally drawn conclusions diverging from those in the cognate disciplines of human performance evaluation (e.g. Fox [17], Grether [59], Ramsey and Morrissey [60], McIntyre [61], Hancock [62], Kobrick and Fine [63], Parsons [64], Ramsey [19], Pilcher et al. [65], Hancock et al. [10], Gaoua [16], Taylor et al. [66], Schmit et al. [67] and López-Sánchez and Hancock [68]).

In order to thoroughly understand thermal effects on cognitive performance, we have systematically reviewed the multidisciplinary literature in this topic as broadly and comprehensively as possible. 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. 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. This synthesis converges on these two prevailing conceptual models—the inverted-U model and the extended-U model. Predicated upon this multidisciplinary foundation, the aims of this review are:

- 1) To clarify the relationship between *performance* and *productivity* and discuss measures of testing thermal environmental impacts on both of them.
- 2) To summarize the influential intervening factors in relation to thermal effects on cognitive performance with a view to explaining the divergence of these two competing conceptual models; the inverted-U and the extended-U.
- 3) To identify potential methodological discrepancies that might account for inconsistent conclusions arising from the competing conceptual models.
- 4) To discuss the practical implications of two conceptual models for the design, engineering and operation of built environments.

2.2 Method of systematic literature search

Peer-reviewed journal articles, conference papers, books and doctoral theses across a wide range of disciplines have been searched with Google Scholar, Science Direct, Scopus, Elsevier, and ProQuest. The keywords driving the searches included: cognitive performance, human performance, task performance, performance response, productivity, cognitive load, cognitive function, mental workload; thermal environment, thermal stress, thermal comfort, temperature, heat, and cold. After reviewing the initial group of papers, we looked at the reference lists of downloaded papers for more specifically relevant papers. The final pool of research papers was drawn from eight major disciplines—psychology, health and medicine, **energy and building**, neuroscience and neurology, human factors and ergonomics, physiology, geriatrics and gerontology, as well as business, economics and management. Table 1 lists 73 key journals from these disciplines for the literature reviewed in this study.

Table 1 Disciplines and journals of the reviewed studies

3. Clarification of Key Concepts

The focus of this paper is on the impacts of moderate indoor thermal environments on human performance, specifically cognitive performance. Before proceeding it is essential to differentiate three related but distinct concepts: (1) human activity, (2) performance and (3) productivity. *Activity* encompasses general pursuits and can involve both psychological and physiological components, but is not directed towards any specific operational goal [64]. In contrast, *Performance* is the outcome of a goal-directed activity where the performers deliberately regulate their behaviour in order to achieve that goal [64]. There is no commonly agreed definition for *Productivity*. Sink [69] and Oseland [70] claim that productivity can be expressed in terms of *efficiency*, i.e. a ratio of input to output. Here we use Parsons’ definition—the extent to which activities generate useful performance in terms of achieving the systemic goals of an organization [64]. According to this definition, productivity of a school student may be represented by their grade point average (GPA), while in a customer service centre, productivity may be expressed as the number of customers served within a specific period of time and how satisfied those customers are with the quality of service they received. The critical point is that productivity can involve many dimensions other than performance *per se*, e.g. social factors such as business and social culture, relationship with colleagues; organizational factors such as organizational structure, job security, workload, management; and personal factors such as injury, loss of sleep, life events, health/well-being, and financial stress, to mention just a few [71,72,73].

An adverse thermal environment may interfere with an activity by affecting the underlying processes involved in the activity. For example, a cold classroom might undermine finger dexterity, thereby negatively affecting students' typing or data-entry activities. However, this may or may not affect performance, depending on how important the affected activity is to the completion of the task [64]. Thus, it may still be possible to maintain stable performance in a computer-based language test if the students' finger dexterity is affected by a cold classroom, but writing skills may not be significantly jeopardized. The role of classroom thermal environments in students' overall productivity, or GPA, could potentially be important, but it is far from obvious given the myriad factors at play, such as the learning culture of the school, the quality of teaching, students' socio-economic backgrounds, not to mention their level of motivation. The effects of thermal environment on human activity, performance and productivity have been illustrated in Figure 1.

Figure 1 The effects of thermal environment on human activity, performance and productivity, adapted from [64] and [73]

It is not easy to measure the effect of thermal environment on human performance, especially complex, realistic job/task in actual workplaces, because there are many variables related to specific tasks in specific contexts that cannot be adequately accounted for. Consequently in performance science, a reductionist approach [64] is often adopted by dividing the job/task into components, and testing the thermal impacts on respective components and factors. Then an approximate prediction can be made about the effects of thermal environment on the overall job/task performance [64,74]. Testing the effect of thermal environment on workers' productivity, especially in office context, will be more problematic. Mawson ([75], p.1) states that "... *productivity is comparatively easy to understand and measure in a manufacturing economy, but as our economies have migrated from manufacturing to service and on to knowledge-based, so the whole issue of assessing productivity has become less clear*". The lack of clarity and agreement in the definition and constituents of productivity also contributes to controversy in selection of appropriate approaches to office productivity measurement [47,70,76,77,78]. Commonly adopted productivity measures include performance tasks, self-perceived productivity, and absenteeism [47,48,70,73,76,77,79,80,81]. However, the validity of these metrics has been questioned. For example, the simulated performance tasks may not realistically reflect the actual job contents in actual workplaces [73,81]; self-perceived productivity cannot reflect the actual productivity [47,73,79]; absenteeism may not be sensitive to the environment [47,73,79].

In the indoor environment field, the terms *performance* and *productivity* are often used interchangeably, and performance measures are also commonly adopted as a proxy for workplace productivity, as evidenced by large number of studies focusing on quantifying "productivity loss" due to adverse thermal environments [52,53,55,56,57,58,71,82,83,84,85]. The effects of thermal environment on productivity cannot be readily quantified, particularly with simulated performance tests. For one reason, simulated performance tasks do not accurately represent the nature of real work carried out in actual workplaces. Furthermore, the effects of other factors of productivity beyond environmental factors cannot be eliminated from the research design (see Section 5.3.4). Several researchers have expressed similar opinions but none have stated it more bluntly than Parsons, an ergonomist who generalised that no general conclusion could be made regarding the effects of thermal environments on productivity [64]. He has pointed out that "*Determining influences of climate on individual performance may be a rather subtle way of investigating productivity. More important effects may be behavioural in terms of sickness or accidents, absenteeism from the workplace or from work altogether, and how easy it is to distract the person from the main task*" ([64], p.404–405). Similarly, Smither [86], Cairns [87], Onyeizu [73], Byrd and Onyeizu [81] have all asserted that social and organizational effects swamp environmental factors.

4. Conceptual Models Linking Environmental Stress and Performance

In environmental psychology *environmental stress* is defined as a negative subjective psychological response to an environmental stimulus [88]. Environmental stress occurs when the demands of the ambient environment overwhelm an individual's capacity to deal with those demands. There are four types of environmental stressors identified by Evans and Cohen [89]: cataclysmic events, stressful life events, daily travails and ambient stressors. Indoor environmental temperature falls into the *ambient stressor* category for building occupants. Despite numerous studies from diverse

disciplines and research groups around the world, consensus on the effects of thermal environmental stress on human performance remains elusive. Various theories and psychological models have been proposed to link ambient stressors with cognitive performance, but the following section is confined to reviewing the two leading contenders.

4.1 The Inverted-U Model

Arousal theory [90,91,92] has been the most influential and ubiquitous model perhaps in all of the stress literature (e.g. [9,10,93,94]). It postulates an *inverted-U relationship* and is alternatively known as the *Yerkes-Dodson law* [95]. 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. [96,97,98,99]). In summary, as the environmental temperature or its subjective perception (e.g. Thermal Sensation Vote - TSV) increases, the arousal level of the performer also increases, which in turn causes cognitive performance to improve. However, after passing through the *single*, critical, or optimal point of ambient temperature (or optimum TSV), cognitive performance starts decreasing with increasing heat load.

In the indoor environmental science domain, arousal theory, with its associated inverted-U relationship, has held sway for several decades, judging by the number of citations it has received. Seppänen and Fisk [50] along with Seppänen et al. [52] have emerged as the most influential studies in this body of literature. In these meta-analyses they collated 24 previously published laboratory and field studies, then fitted an inverted-U relationship to the summary data. Their fitted model shows performance increasing as temperatures increased towards 21.6 °C, then decreasing in temperatures beyond 22 °C (Figure 2). The same inverted-U relationship is mirrored in the *ASHRAE Handbook of Fundamentals* [27] and *REHVA Guidebook No. 6* [26], which are widely regarded as the definitive guideline for HVAC engineers the world over. Instead of predicting performance from room temperature, as in Seppänen et al. [52], the graph in the *ASHRAE Handbook* shows the x-axis as room temperature relative to the optimal comfort temperature T_c or neutrality for the group. Despite the very wide scattering of actual data points in the meta-analysis (Figure 3), *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 3).

Figure 2 Relative performance vs. temperature adapted from Seppänen et al. [52]

Figure 3 Relative performance of office work vs. deviation from optimal comfort temperature T_c adapted from *ASHRAE Handbook of Fundamentals* [27]

Several other indoor environmental scientists have correlated cognitive performance metrics with Thermal Sensation Vote (TSV) instead of indoor temperature, obtaining broadly consistent results to (*ASHRAE Handbook of Fundamentals*), as shown in Figure 4. A notable exception is Jiang et al. [100] in which pupils’ attention, perception, memory and comprehension, and logical reasoning performance were examined, and finding that response efficiency peaked at TSV of -1.4 (between thermal sensations of “cool” and “slightly cool”), which was much lower than the values observed for adults. Regarding adult studies, the model of Jensen et al. [56] indicated optimum performance of an arithmetic addition task occurring when the TSV was -1 (*slightly cool*), which was lower than that established by Lan et al. [53] who found the optimum performance corresponded with a close-to-neutral TSV = -0.25 for arithmetical calculation, typing, logical reasoning and memory tasks. This was also echoed by the Geng et al. [83] model’s optimum performance on tests of concentration, arithmetic calculation and memory, occurring close to TSV=0, and in further support, Cui et al. [101] found the maximum memory typing performance occurred at TSV= +0.14.

Recognising that room temperature is only one of the causal factors affecting the human heat-balance, researchers such as Kosonen and Tan [55] has replaced the independent variable in their research designs with integrated indices of

thermal environment such as the Predicted Mean Vote (PMV)¹, which is expressed on the same 7-point Likert scale as TSV (Figure 4). Kosonen and Tan [55] re-analysed research data of Wyon et al. [102], and Wyon [48,103] and reported that optimum level of office productivity assessed by thinking and typing tasks occurred when the PMV value was -0.21 , corresponding to an operative temperature of $20\text{ }^{\circ}\text{C}$ for participants wearing relatively heavy indoor clothing (estimated to be 1.16 clo).

Figure 4 The inverted-U relationship of cognitive performance proposed in various studies using thermal sensation vote as the independent variable instead of temperature (data from Kosonen & Tan [55]; Jensen et al. [56]; Lan et al. [53]; Cui et al. [101]; Geng et al. [83]; Jiang et al. [100])

4.2 The Extended-U Model

The extended-U model, initially proposed by Hancock and Warm [104], is also referred to as the *Maximal Adaptability Model*. In contrast to the inverted-U model, the central tenet of the extended-U model is that human performance remains relatively stable across a broad range of acceptable temperatures, but it rapidly deteriorates at the boundaries of thermal acceptability (Figure 5). Thermal stress exerts its adverse impacts on performance by consuming and ultimately depleting the performers' attentional resources (see [105]). 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 [106]. Because of the central role played by psychological adaptability this region is referred to as the psychological zone of maximal adaptability in Figure 5. When the stress level continues to increase, human performance deteriorates as attentional resources begin to be depleted. This is represented in Figure 5 by the dashed line at the boundary of the psychological zone of maximal adaptability. Further increase in stress intensity pushes the performer beyond their physiological zone of maximal adaptability toward incipient life-threatening circumstances.

Figure 5 The extended-U model linking stress and human performance [93,104]

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 (e.g. [10,16,19,65,66,67]), none of which were published in the HVAC engineering and building science outlets. For example, Ramsey [19] summarized a large collection of relevant 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 brief exposures. Pilcher et al. [65] categorized 22 studies into five wet-bulb globe temperature (WBGT²) ranges, and found that the greatest performance decrement occurred in both the coldest ($< 10\text{ }^{\circ}\text{C}$ WBGT or $11.5\text{ }^{\circ}\text{C}$ air temperature at 50% RH) and hottest conditions ($\geq 32.2\text{ }^{\circ}\text{C}$ WBGT or $34.8\text{ }^{\circ}\text{C}$ air temperature at 50% RH), while the broad central range spanning from 21.1 to $26.6\text{ }^{\circ}\text{C}$ WBGT (23 to $29\text{ }^{\circ}\text{C}$ at 50% RH) had no discernible effect on performance, confirming predictions from the extended-U model. In Hancock et al.'s [10] meta-analysis of 49 separate studies providing 528 effect sizes, the original studies were classified into four effective

¹ Predicted Mean Vote (PMV) is a comfort index that combines the effects of four environmental parameters (air temperature, mean radiant temperature, humidity and air speed) plus two personal parameters (metabolic heat production and clothing insulation level) [27]. PMV is expressed on the same 7-point thermal sensation scale as TSV.

² Wet-bulb globe temperature (WBGT) index: an environmental heat stress index that combines dry-bulb temperature t_{db} , a naturally ventilated (not aspirated) wet-bulb temperature t_{wb} , and black globe temperature t_g , is widely used for estimating the heat stress potential of industrial environments [27]. WBGT is commonly approximated as $0.7 \times t_{wb} + 0.3 \times t_{db}$ [65].

temperature (old ET³) ranges: below 25.7 °C, 25.7 °C–29.4 °C, 29.4 °C–35.2 °C, and 35.2 °C and above. Hancock et al. found that, “... with the exception of the lowest temperature range, it is clear that the effect size⁴ 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” ([10], p.862) and this pattern represents a core feature of the extended-U theory of stress and performance. There’s also evidence accumulating from the indoor environment domain that is consistent with the extended-U model (e.g. Tanabe & Nishihara [107]; Witterseh et al. [108]; Fang et al. [109]; Haneda et al. [110]; Lan & Lian [111]; Lan et al. [57]; Lan et al. [58]; Melikov et al. [112]; Cui et al. [113]; Maula et al. [114]; Zhang & de Dear [115]; Zhang et al. [116]; Schiavon et al. [117]; Liu et al. [118], although the original authors may not have interpreted their findings within the extended-U framework at the time of their publications.

5. Conflicts between the Different Models

Previous literature reviews and formal meta-analyses have identified a number of potential explanations of the apparent contradictions between different studies of moderate thermal environmental effects on cognitive performance (e.g. [9,10,16,19,66,119,120]). Besides potential confounders there are also methodological differences that have also contributed to apparently contradictory conclusions.

5.1 Confounding Factors Mediating Thermal Effects on Cognitive Performance

Numerous variables that one might suspect of having an influence on mental performance were necessarily overlooked when comparing results from such a diversity of research designs. These potential confounders can be classified as environment-related, task-related, and performer-related factors.

5.1.1 Environment-related Factors

- Intensity of Thermal Stress

More extreme temperature exposures can be expected to result in larger performance decrements than moderate temperatures [65]. Environments that are hot enough to induce increases in body core temperature are consistently reported to adversely affect task performance [62,99,121,122,123,124,125,126,127,128,129]. Hancock [62] suggested that cognitive performance decrements in heat were due to *dynamic* increases in deep body (core) temperature and proposed that any thermal environment that led to a rate-of-increase in core temperature of 0.22 °C/h impaired (dual tasks), 0.88 °C/h degraded (tracking tasks) and 1.33 °C/h reduced (simple mental task) efficiency. This interpretation aligns with Ramzjou and Kjellberg’s [130] report of a negative correlation between performance on both a simple reaction time task and a serial four-choice reaction time task, and the rate-of-change in core temperature.

Earlier studies of cold environments and cognitive performance have indicated that even moderate cold exposures can have a negative effect on cognitive function [131,132,133]. To be specific, cold exposures ranging from extremes of –20 °C up to a moderate 10 °C have led to statistically significant decrements in memory performance [11,134,135,136], vigilance [137], reaction time [11,136,138,139], learning and reasoning [65,136], and decision-making [11,140]. However, there are also recent studies that have reported no change of vigilance or multiple-choice reaction performance at 0 °C [128], and no change of psychomotor vigilance, four-choice reaction time, match-to-sample efficiency, or grammar performance at 10 °C [141].

- Duration of Exposure

Previously published research findings are inconsistent on the question of how duration of exposure to thermal stress affects cognitive performance. Ramsey and Kwon [142] as well as Ramsey [19] concluded that the duration of exposure to heat did not have influence on performance, but Pilcher et al. [65] concluded that performance deteriorated more under

³ Effective temperature (old ET): the first version of the ET environmental index that combines the comfort effects of both temperature and humidity. Because of the transient comparative exposures in the ET index’s underlying chamber experiments, ET tends to over-emphasize the comfort significance of humidity relative to steady-state exposures.

⁴ The effect size statistic represents how many standard deviations the mean dependent variable score for the experimental group differed from that of the control group.

short-term temperature exposures compared to prolonged exposures, while Hancock et al. [10] and Yeganeh et al. [143] reported completely the opposite, with greater decrements in cognitive performance during prolonged exposure to thermal stressors. Hancock et al. [10] claimed that this relationship broke down in the very longest time intervals — exposures lasting longer than 3h were as benign as exposures shorter than 1h [10]. However, the same researchers also reported an interaction effect between duration and intensity of heat exposure: thus, a shorter exposure to heat results in greater performance degradation compared to longer exposures, implying some form of habituation to heat (discussed later).

Inconsistent duration of exposure effects could be partly due to the diverse task types under investigation. López-Sánchez and Hancock [68] reported distinct task-specific patterns of performance deterioration linking temperature and exposure time, e.g. for the same probability of impaired performance represented by isodecrement curves, mental and vigilance tasks demonstrated more prominent temperature effects on exposure time in high temperatures than more comfortable temperatures.

- Thermal transients

A handful of studies have examined cognitive performance under transient thermal exposures—temperature ramps, drifts and cycles [38], and they have reported contradictory findings. Studies by Wyon et al. [144,145] and Zhang and de Dear [115] are the only studies focused on the cognitive performance during environmental temperature cycles. The Wyon et al. [145] climate chamber study of 16 participants found that small, rapid swings around the preferred temperature resulted in decreased efficiency and speed of mental arithmetic, while larger amplitude, slower swings were associated with higher work speed and accuracy at least equal to that obtained under steady-state exposures. In contrast, the larger climate chamber study of 56 participants by Zhang and de Dear [115] failed to detect any such statistically significant difference in university students' memory, concentration, reasoning or planning performance during exposure to temperature cycles of various amplitude and frequency.

Nor have previous laboratory studies on moderate temperature ramps yielded any consistent findings on cognitive performance [146,147,148]. In a 1.5 °C rising temperature ramp over a 2.5 h interval, Newsham et al. [146] reported that some tasks such as solving anagrams, evaluating resumes, and vigilance exercises were negatively affected, whereas satisfaction of performance, time taken to rate magazines, motivation and short-term memory were all *improved* during exposure to the same temperature ramp. Kolarik et al. [147] investigated the effects of different temperature ramps ranging between 17.8–26.8 °C on office work performance, and found that individuals read more quickly but detected slightly fewer mistakes while proof-reading under the rising temperature ramps. In contrast, downward temperature ramps positively influenced reading speed, accuracy, as well as comprehension. In contrast Schellen et al. [148] examined the effects of similar moderate temperature ramps (17–25 °C) on younger and older adults' text typing and arithmetic addition performance, but failed to detect any significant effect in either age group of subjects.

Muller et al. [11] investigated the effects of large temperature step changes (25→10→25 °C) on cognitive performance and found significant decrements in working memory, choice reaction time, and executive function during the cold exposure (10 °C). Moreover, these impairments did not disappear until 60 min after the 25 °C rewarming period started.

5.1.2 Task-related Factors

- Task Type

There is broad consensus that the impact of heat stress on cognitive performance is highly task dependent, with simple tasks that require less attention being less susceptible to heat effects than more complex tasks [9,10,19,57,65,100,120,143,149,150,151]. For example, studies using functional Magnetic Resonance Imaging (fMRI) to examine the brain activities found that passive heat exposures (45–60 min at 50 °C, 40% relative humidity) did not affect the performance of simple mental tasks such as alerting and orienting, but complex executive function, especially the efficiency of resolving conflict was adversely affected [152,153]. The mediating effect of task type for cold stress on cognitive performance has also been reported in a few studies showing varied performance threshold temperatures and patterns of response for different tasks [18,134,139,154,155], but further studies and validation are needed before definitive conclusions can be drawn.

Previous reviews have often categorized performance studies into different types of tasks. Ramsey [19] proposed two broad categories: (1) mental, cognitive, simple perceptual motor, sensory, time estimation, reaction time, and (2) other perceptual motor tasks including tracking, vigilance, vehicle or machine operation, complex or dual tasks. Pilcher et al. [65] categorized performance tasks into four groups: (1) reaction time tasks, (2) attention/perceptual tasks, (3) mathematical processing tasks, and (4) reasoning/learning/memory tasks. Hancock et al. [10] divided performance tasks into three categories, i.e., perception, psychomotor, and cognitive tasks.

Pilcher et al. [65] concluded that thermal environments have different effects on different types of tasks, with thermal environments higher than 26.7 °C WBGT (29.0 °C at 50% RH) having the greatest negative impact on attentional/perceptual tasks and mathematical processing, whereas cold stress below 18.3 °C WBGT (20.2 °C at 50%) negatively affected reasoning/learning/memory tasks the most. Hancock et al. [10] concluded that cognitive performance was generally more stable under thermal stress conditions compared to perceptual and psychomotor performance, and that cognition could actually benefit from brief exposures to moderately cold temperatures.

Recent brain research also shows, that different cognitive functions are affected differentially by thermal stress. Gaoua [16] pointed out that different cognitive tasks activate different regions of the brain [156,157]. Recent animal researches [156,158] have reported brain temperature fluctuations of 3–4 °C during different naturally occurring physiological and behavioural activities even at static thermal environments. For example, resting rats have significantly lower hippocampus temperature (about 0.7 °C) compared to the medial pre-optic area of the hypothalamus [158]. Temperature of both brain areas is directly correlated with core temperature and increases in a linear fashion [158]. This means at the same core temperature, different brain areas would have different absolute thermal load, which is to say, thermal stress could potentially affect cognitive capacity to varying degrees depending on the specific brain areas being engaged [16].

- Task Complexity

Cognitive tasks have often been characterised as either “simple” or “complex”, but even this seemingly straightforward categorization has proven to be controversial and problematic [157]. Taylor et al. [66] provided a list of cognitive tasks (see Table 2) that are generally agreed to be either simple or complex, based on a survey of the literature [9,16,142,159,160] but then issued the caveat that such classifications should be interpreted with caution. Gaoua [16] pointed out that previous literature conflated “task type” and “task complexity” into one categorization. This differentiation tends to ignore the differential cognitive loads exerted on respective brain regions. It was therefore suggested that future work should look at both task type as well as complexity by manipulating complexity within the same types of task [16].

Table 2 Categorization of simple and complex cognitive tasks [66]

5.1.3 Performer-related Factors

- Skill Levels of the Performer

Researchers from diverse domains generally agree that performers of a higher skill level prove less susceptible to performance decrements under thermal stress (e.g. [9,16,19,62,66,142,161]).

According to cognitive load theory (CLT) of instructional design [162,163,164,165,166,167,168,169], cognitive architecture comprises Long-Term Memory (LTM) and Working Memory (WM), with the latter being severely limited in both capacity [170,171,172] and duration [173]. When dealing with novel information, limited WM resources often fail to meet the demands of complex cognitive tasks. However, once the new information has been assimilated, processed, rehearsed, and stored in LTM, the constraints arising from limited WM resources are largely eliminated. Newly acquired information in LTM must be processed consciously and with considerable effort, but with increasing practice and familiarization, this information can be used with diminishing conscious processing effort, and finally, automatically [174,175,176]. With this *automated processing*, cognitive tasks can be carried out virtually unconsciously without the need of mental effort, further reducing the load on WM and the limitations of WM ultimately disappearing altogether for the most experienced performers working from previously learned information stored in LTM.

- Gender and Age

Hancock and Vasmatazidis [9] emphasized the importance of gender when investigating thermal effects on cognitive performance. Methodological shortcomings notwithstanding, previous studies seemed to suggest that females' performance was generally less vulnerable to thermal stress than males'. Wyon et al. [177] observed a significantly slower response speed in male participants' multiplication task performance at 28 °C compared with either lower or higher temperatures, while female participants' performance on the same task was unaffected at 28°C. Tanabe and Nishihara [107] reported no significant difference in females' performance in typing, addition, cursor positioning and Walter Reed Performance Assessment Battery Test at operative temperatures of 25.5 °C, 28 °C and 33 °C, but their male participants' typing performance at 25.5 °C was significantly lower than at 28 °C and 33 °C, and their performance of the "four choice serial reaction time" test at 33 °C was significantly lower than at 28 °C.

Drag and Bieliauskas' [178] review indicates that aging is associated with progressive decline of certain cognitive functions, such as processing speed [179,180], complex attention [181,182], executive functions [183,184], language [185,186], episodic memory [187], source memory [188], prospective memory [189], and visuospatial functioning [190,191]. However, there is no research evidence demonstrating that thermal environment affects cognitive performance of young or elderly adults differently. In a controlled trial, Trezza et al. [192] found that memory, attention and processing speed of 68 healthy, elderly adults (mean age 73 years, 69% female) exposed to a hot environment with air temperature of 32 °C was not significantly different from that observed during exposure to a neutral air temperature of 24 °C. This null finding aligned with that of Schellen et al. [148] who noted that the typing and addition performance of the elderly was not significantly different during a constant temperature of 21.5 °C compared with a temperature drift ranging between 17 °C and 25 °C. The null effects are those that would be predicted by the extended-U model.

- Thermal Acclimatization

Several previous studies have demonstrated that in hot environments, acclimatization to heat improves the efficiency of thermal physiological response of sweating and shortens onset time [193,194,195,196,197], with the net effect of averting core temperature excursions. However, effects of acclimatization on cognitive performance have not been sufficiently investigated, mainly because it is uncommon for cognitive performance studies in heat to report participants' state of acclimatization [10,19]. Radakovic et al. [198] studied the impacts of both active and passive acclimatization procedures on participants' physiological and cognitive responses during heat stress, and found no effect on attention tasks, however response accuracy in complex tasks was reduced for participants with no acclimatization. Gaoua [16] has pointed out that habitual acclimatization does not seem to be an important confounder when investigating cognitive performance in heat, unless a specific acclimatizing procedure is being implemented.

- Hydration Status

Mixed findings have been reported concerning the role of hydration status in thermal effects on cognitive performance. Decrements in cognitive processing have been associated with dehydration beyond 2% [151,159,199,200,201,202], yet others have reported no meaningful impact [141,203,204,205,206]. Despite this, it would be prudent for the hydration status of all participants to be recorded in future thermal performance studies.

5.1.4 Interactions between Environment, Task and Performer

- Core Temperature, Skin Temperature and Thermal Comfort

The performers' core temperature, skin temperature, and thermal comfort/discomfort result from complex interactions between their thermal physiological responses, their behaviour, and their immediate physical environment. As noted earlier, dynamic increases in deep-body (core) temperature are thought to impair cognitive performance [15] but more recent studies have demonstrated that accompanying changes in skin temperature are also implicated [16,66,207,208]. In the Gaoua et al. study [208] participants were exposed to a room temperature of 50 °C at 30% RH for up to 15 min, resulting in a significant increase in skin temperature of up to 3 °C, but core temperature remained unchanged. It was found that simple tasks were unaffected, whereas complex cognitive task performance significantly deteriorated during these brief exposures to heat. Increasing skin temperature was interpreted as a mediating physiological variable that alters the subjective state of an individual and impairs effective decision-making. In a similar experimental design, Gaoua et al.

[207] applied cold packs for head cooling and found that some of the complex cognitive functions were preserved unchanged while other studies reported inconsistent effects of head cooling on cognitive performance [127,129,209].

The sensitivity of complex cognitive function to changes in skin temperature and thermal comfort/discomfort could be related to the *alliesthesia* effect, initially proposed by Cabanac [210] and subsequently developed by de Dear [211] and Parkinson and de Dear [212] into a conceptual model of dynamic and local thermal comfort. Any environmental stimulus that reduces load-error on the thermoregulatory system, or any of the body's other homeostatic systems, will be pleasantly perceived—positive alliesthesia. Conversely any environmental stimulus that enlarges load-error on the thermoregulatory system is perceived as an unpleasant stimulus—negative alliesthesia. Several transient thermal comfort studies aligned with the Gaoua et al. findings [207,208]. For example, Zhang and de Dear [115] reported a negative correlation between planning performance (complex cognitive task) and *rate* of environmental temperature increment, as well as a positive correlation between performance on the same cognitive task and thermal acceptability during environmental temperature cycles that started from 24 °C (temporal alliesthesia). Schiavon et al. [117] found that the negative impacts of elevated environmental temperatures (29 °C) on cognitive performance were ameliorated when subjects were given access to a desk fan that they could control (spatial alliesthesia). These experimental studies, albeit limited in number, are consistent in their suggestion that both the spatial and the temporal variants of positive thermal alliesthesia can ameliorate the negative impacts of thermal stress on the performance of complex cognitive tasks. This begs the question as to whether *negative* alliesthesia may exacerbate performance decrements, but this has not yet been addressed in the thermal environment and performance literature. What is promising is that these results encourage the idea that technologically simple and affordable Personal Comfort Systems (PCS) [213,214,215,216] may be feasible in preserving both comfort and cognitive efficiency across a range of moderate thermal environments.

- Other Interaction Effects

Mental effort can be assumed to reflect the interaction between the performer and the task characteristics, serving as an important mediating factor. Intuitively we know how strong motivation and mental effort can override the effects of stress on our performance even in extreme environmental conditions, and there is plenty of experimental evidence demonstrating this in the thermal environmental performance literature (e.g. [9,57,58,101,217,218]). Other interactive effects such as task type and exposure duration, task type and intensity of thermal stress, to mention just a few, may also influence both the magnitude and direction of thermal stressors on performance [9,10].

5.2 Causal Mechanisms Behind the Two Models

The underlying mechanisms for changes in cognitive function during exposure to uncomfortable thermal environments are not yet fully understood, but numerous reviews across various disciplines have offered hypotheses and rationales (e.g. [9,10,15,19,161,166,167,219,220]).

The underlying rationale for the inverted-U model can be likened to *Environmental Determinism Theory* (EDT) prevalent in social ecology. Environmental determinism asserts that “*human activity, culture, and physical and mental characteristics are, at once, informed and inhibited by the geographical and climatic conditions of the physical environment*” ([221], p.720). For example, one of its earliest origins—the treatise “*airs, waters, and places*”, claims that people's health, personality and physique are dependent on how the physical environment affects their bodily humors, i.e. blood, yellow bile, black bile and phlegm which regulate mood, temperament and physical well-being. The European understandings of environmental influences on human beings have been deeply influenced by this Hippocratic notion [221]. By analogy, the inverted-U model assumes that thermal environment and thermal stress directly *determine* the task performers' cognitive efficiency, regardless of other factors, and this reduces to a *dose-response relationship* [56]. However, this assumption oversimplifies the complex, dynamic and integrated “internal” mechanisms of human response to environmental stimuli. From an environmental ergonomist's angle, Parsons ([15], p.582) pointed out that “... *the human body is not a passive system that responds to an environmental input in a way that is monotonically related to the level of the physical stimulus. Any response depends upon a great number of factors.*” He further elucidated three layers. First, if viewed in engineering terms, the “transducers” of the body—the human sensory organs such as eyes, ears, etc.—each have their own specifications and response characteristics when stimulated by their relevant physical environmental element. Second, human bodies are not *passive systems*, but rather react homeostatically, constantly adjusting and regulating their physiological systems and behaviours to *adapt* to the environment. Third, the way people perceive and

respond to environmental stimuli depends on many other factors such as their previous experience, expectations, cultural context, current emotional states, to mention just a few, and these are both inter-individual differences (e.g. gender, age, personality) and intra-individual differences (e.g. acclimatization, emotional state). Parsons' perspective intersects with Hancock's view [222] that engineering approaches regard building occupants as if they are insensate objects and "while simple linear equations describe heat exchange, they do not capture the subtlety and nuances of behavioural regulation, the prime goal of which is the maintenance of comfort" ([222], p.1860). The importance of behavioural regulation in achieving thermal comfort is also emphasized by the adaptive comfort theory [223,224], which deems the building occupants as being interactive agents in a person-environment system via multiple feedback loops including behavioral adjustment, physiological acclimatization, psychological habituation, and probably most important of all, expectation adjustment.

Not surprisingly, many researchers in the field of psychology have levelled criticisms at arousal theory and the inverted-U model as an *explanation* of the relationship between stress and performance (e.g. [93,94,225,226,227]). The main arguments fall into two categories: first, Yerkes and Dodsons' original experimental study [95] was about animal learning, and the researchers themselves connected none of their observations with *stress and performance*. Second, the inverted-U relationship is an over-simplified, fundamentally flawed proposition, and the unitary arousal notion is incongruent with known physiological and psychological effects, and emerging behavioural response data (e.g. [228,229,230,231,232]). And yet, despite these glaring theoretical shortcomings, Arousal Theory continues to be taught as a fundamental "law" in psychology and the broader realms of human behaviour research: from product development teamwork [233] to the piloting of aircraft [234], from competing in sport [235] to solving complex cognitive puzzles [236].

The mechanisms underlying the extended-U model are well elaborated by the "cognitive load" construct from the Cognitive Load Theory (CLT) of instructional design (e.g. [161,166,167,237,238]). In CLT the physical environment, task, and performer are considered to be three *causal factors* pertaining to cognitive load, which is also affected by two-way and three-way interactions between the three factors. The construct of cognitive load is schematically presented in Figure 6. The major determining characteristics of environments, tasks, and performers, along with key interaction effects have been briefly discussed here. With regard to its assessment, cognitive load can be conceptualized into three dimensions, namely mental load, mental effort, and performance [161,166]. Mental load is a task-centered, subject-independent dimension. Mental effort reflects performers' internal reaction to the mental load, such as their internal goals, motivation level and so on. As previously discussed, novel information in WM or newly acquired information in LTM must be processed consciously and with considerable mental effort, known as "controlled processing". "Automatic processing" happens when the requisite knowledge is well known and stored in the participant's LTM so that the task can be accomplished unconsciously without mental effort. Consequently, assessment of cognitive load based on mental effort reflects the amount of controlled processing in which the performer is engaged [174,175]. Performance is the output of the mental load and mental effort, and can also assess cognitive load.

Figure 6 Mechanism behind the extended-U model applied to relationships between thermal environments and cognitive load: thermal environment serves as **one** of the causal factors of cognitive load (modified after [161])

As have been discussed in Section 4.2, environmental stress may increase cognitive load by competing and consuming limited attentional resources, which could have been alternatively allocated to the task *per se*. Nonetheless, whether or not the *performance* is implicated still depends on other intervening factors. If the task induces low mental load, and there are sufficient attentional resources for both the task and the imposed environmental stress, performance efficiency will not be affected. Similarly, extra mental effort can cope with increased environmental stress in order to maintain the same level of performance; this extra effort will not be needed if the performer achieves *automatic processing* in carrying out the task. Besides, other environment-, task- and performer-related factors along with the two-way and three-way interactions (discussed in Section 5.1) may also mediate the effect of environmental stress on performance.

In the human-machine-systems research domain there is an analogous concept to *cognitive load*, termed *mental workload* [219,239,240,241]. Johannsen [220] discussed the three functionally relatable attributes of mental workload and its assessment (as shown in Figure 7). These attributes echoed the assessment factors of cognitive load in CLT illustrated in Figure 6. Input load can come from three major sources: *environment* (such as temperature, noise, smell); *design and situation* (e.g. characteristics of display and control devices); and *procedures* (e.g. task sequence, task duration, etc.). Operator effort is determined by the input load, characteristics of the performer, and the requirements of the given task. The performer characteristics can comprise many factors ranging from relatively stable ones such as psychophysical characteristics, general background and personality, through to fluctuating ones such as experience, motivation, and attentiveness [219].

To sum up, both the CLT theory and Mental Workload theory confirm that the physical environment serves as **one** factor that induces cognitive load (mental workload), but there is not a dose-response relationship between *environment* and *performance* due to many intervening factors.

Figure 7 Assessment of mental workload by input load, operator effort and performance [219,220]

5.3 Methodological Discrepancies

As Hancock and Ganey [93] have pointed out, the enduring popularity of the inverted-U relationship as an explanation of the effects of stress on performance resides in its intuitive appeal, aligning with “common sense” interpretations of the issue. Nevertheless there are methodological shortcomings that weaken, if not invalidate the empirical evidence adduced to support the inverted-U model in the indoor environmental science and engineering literature.

5.3.1 Three Primary Approaches to Measuring Cognitive Load

Previous researchers [242,243,244,245] have identified three fundamentally different approaches to the measurement of cognitive load: (1) primary task performance; (2) subjective perception of cognitive load; (3) physiological response, but studies where they have been used alongside one another indicate divergence.

- Primary Task Performance

Primary task performance (Figure 7) has been expressed variously as by probability of error, response time, response accuracy, response consistency, and response range, but speed and accuracy are the most commonly used forms of assessment, particularly in field-based research (see e.g. [13,246,247]). Lan et al. [53,248] pointed out that in indoor environmental science research, response speed is used more often than response accuracy to quantify performance. For many types of tasks there exists a speed-accuracy trade-off [248,249]. Hancock et al. [10] concluded that heat affects response time and accuracy differently: no matter the heat is above or below the 29.4 °C old ET threshold, response accuracy will be uniformly affected by heat stressors; as a contrast, no effect for heat on response time has been observed below the threshold. Yeganeh et al. [143]'s meta-analysis generally corroborate Hancock's finding that response accuracy is more affected by heat than response time.

- Subjective Perceptions of Cognitive Load

The concomitant changes in *mental effort* (Figure 6) might not be self-evident in work performance measurements since people tend to adjust to changes in task demands in ways that protect their performance [218]. In this case, self-reported perceptions can be helpful. Commonly used subjective measurements of cognitive load include NASA-TLX and SWAT. NASA Task Load Index (TLX) relies on a multidimensional construct to generate an overall workload score according to weighted average ratings on six subscales: mental demand, physical demand, temporal demand, performance, effort, and frustration level [250]. The Subjective Workload Assessment Technique (SWAT) described by Reid and Nygren [251] also requires participants to rate the workload of a task, but uses a different suite of rating dimensions: time load, mental effort load and psychological stress load. Parsons [15] pointed out that subjective ratings are easy to implement and well suited to the assessment of *psychological responses*. They can also be useful when the contributing factors to a response

are unknown. However, subjective ratings are often not appropriate for assessing *effects on health* since the environmental stressor can also interfere with the capacity to make a reliable subjective assessment.

- Physiological Responses

Due to the development of brain imaging technologies in recent decades there are many new approaches that visualize brain activities and directly measure the physiological responses under mental workload, including electroencephalogram (EEG) [252], heart rate and heart rate variability [253]. Employing these measures leads to a better understanding of the neural architecture of cognitive abilities.

The raw electroencephalogram, or background EEG, is indicative of brain activity levels [254]. Liu et al. [153] and Sun et al. [255] adopted functional Magnetic Resonance Imaging (fMRI) to examine alterations of the brain blood flow and how different environmental conditions affect attention network. Functional Near-Infrared Spectroscopy (fNIRS) provides safe and continuous monitoring of changes in both blood oxygenation and volume that are related to human brain function. Compared to other neuroimaging techniques such as EEG and fMRI, fNIRS is a good compromise between spatial and temporal resolution. fNIRS has a higher spatial resolution than EEG, and is less susceptible to motion-related artefacts, blinking or eye movements, compared to EEG [256]. Previous studies reveal that physical and mental workload has a clear impact on Electrocardiography (ECG), or heart rate and heart rate variability [257,258,259,260]. Increased heart rate and decreased heart rate variability are usually associated with mental exertion [261].

It is worthwhile noting that the above three approaches of cognitive load measurement—primary task, subjective perceptions and physiological responses, do not always agree with each other when they are applied concurrently. As has been observed by Hancock et al. [245], results from the three approaches could agree with each other (*association*), or may not correlate (*insensitive*), or contradict each other (*dissociation*), with each circumstance commonly being reported in different research studies [262]. For example, Lan et al. [58] adopted all three approaches in evaluating the effects of temperature on cognitive load. The primary task results were not significantly different between various temperature conditions of their experimental design, yet the participants' subjectively rated cognitive load was higher in the moderately uncomfortable environment, and their EEG and ECG results displayed significant differences between comfortable and warm conditions. Conflicted responses often leave researchers in a methodological quandary as to which approach and corresponding results to trust and to report, and which, if any, to ignore without appearing to “cherry-pick” the data [245]. The interpretation of results from divergent cognitive load measures has undoubtedly contributed to the contradictory conclusions throughout the literature. For example, the meta-analyses conducted by Pilcher et al. [65] and Hancock et al. [10] only included *primary task performance* results, expressly precluding papers based on subjective ratings and physiological measurements. This uniformity of cognitive load measurement in their meta-analyses goes some way towards explaining why they found relatively stable performance across a wide range of thermal environments. In the indoor environment area, researchers tend to put greater emphasis on perceived performance and subjective ratings as opposed to objective performance metrics (e.g. [57,58,109,111]). Despite their objective performance measurements failing to show any significant difference between exposure temperatures, Witterseh et al. [108], Lan and Lian [111] and Lan et al. [53] focused their interpretation on subjective ratings such as self-estimated performance, emotional state, motivation level, health symptoms, well-being, and perceived mental workload. They concluded that “*office work may generally be performed considerably less well in... and less well at subjectively warm air temperatures than at cooler temperatures*” ([108], p.39), “*... the performance of neurobehavioral tests decreased when the thermal environment deviated from neutral condition*” ([111], p. 2208), and “*... thermal discomfort caused by high or low air temperature had negative influence on office workers' productivity*” ([58], p.36). The issue of exactly how to filter and interpret cognitive load data from different approaches falls outside the scope of this review, but it seems fairly obvious that it should take at least some of the blame for the inconsistencies plaguing the literature on thermal effect on cognitive performance.

5.3.2 Plethora of Cognitive Task Types and Levels of Complexity

The performance results used in the meta-analysis by Seppänen and Fisk [50] as well as Seppänen et al. [52] were drawn from a variety of environments, including call centres, apparel factories, classrooms, offices, laboratories, to mention just a few, and the performance metrics included the number of customer service calls per hour in the case of the call centre

studies, rate of sewing piece-work, learning, text typing speed and error rate, error detection in proofreading, arithmetic addition, creative thinking, letter searching, number searching, memory tests, and vigilance tasks. The metrics spanned the gamut of human performance domains—manual, reaction time, attention, perceptual motor, mathematical processing, reasoning, memory, and executive function. As noted earlier, the magnitude of performance decrements under heat or cold stress, and the temperature thresholds at which they occur, depend on both the type and complexity of the cognitive task in question. Consequently pooling performance data from diverse cognitive tasks (e.g. [50,52,53,57,83,84,100,111]) seems likely to have contributed to both the confusion and the contradictory conclusions across the literature on thermal effects on cognitive performance in the indoor environment.

5.3.3 Statistical Analyses

Another potential explanation for discrepancies between stress-performance models is divergent analytical approaches adopted by different researchers. For example, Seppänen et al. [52] indicated that some studies in their meta-analysis relied on multiple performance tests from each subject, and so results might be highly correlated. Despite acknowledging that the assumption of independence of errors was violated, Seppänen et al. [52] conducted simple regression analysis on repeated-measure data to develop a performance-temperature relationship, as have several other researchers in this domain. They typically developed a cubic or quadratic relationship (Equation (1)) between performance and temperature (or thermal sensation), speciously supporting the inverted-U model [53,55,56,83,100,101,111,263,264].

$$RP = aTSV^3 + bTSV^2 + cTSV^1 + d \quad \text{Equation (1)}$$

where RP denotes relative performance and TSV is thermal sensation vote (−3 to +3 on the ASHRAE seven-point thermal sensation scale). Some studies use PMV (also on the ASHRAE seven-point scale) or air temperature as the predictor.

There are two types of problems with this statistical analysis. First, analysing data sets containing hierarchical structures resulting from within-subject research designs, as if they are all on the same level, risks both interpretation and statistical errors [265,266]. In particular, if correlated or clustered data are analysed using a single-level model and there is dependence of errors, the risk of *Type I* error (rejection of a null hypothesis when it is actually true) can dramatically increase [267]. Therefore, findings of significant effects of treatment variable cannot be trusted when independence of errors has been assumed without justification [267,268]. Second, univariate regression as in Equation (1) with TSV or air temperature as the only predictor overlooks effects of other predictors (confounding variables) on cognitive performance such as subjects' age, sex, sequence effects, etc.

To conduct regression analysis with correlated or clustered data, it is recommended to use *Generalized estimating equations (GEEs)* or *Generalized linear mixed models (GLMMs)* [268]. The former approach focuses on estimating the average response over the *population*, while the latter approach can make inference about *individuals* [268]. GLMMs are also referred to as *multilevel models*, *mixed models*, *random coefficient models*, and *hierarchical models* [269]. To illustrate the effect of different statistical analytic strategies on the same set of performance data, we have re-analysed the results reported in Experimental 1 of Zhang and de Dear [115] using (a) single-level univariate regression analysis as shown in Equation (1), and (b) the more appropriate multilevel models with significant sequence effects adjusted. The analysis (a) yielded a statistically significant *quadratic* regression model between reasoning performance score and thermal sensation vote ($p = 0.031$, $R^2 = 0.015$)— so the research hypothesis is mistakenly accepted. In contrast, when the same data are reanalysed with multilevel models with sequence effects adjusted (b), no significant relationship was detected (shown in Zhang and de Dear [115] Table 5: Reasoning skills) —so the null hypothesis is correctly accepted.

5.3.4 Construct Validity/Sensitivities of the Performance Tests

Variations in construct validity and sensitivity of performance tests may also have contributed to contradictory research results being reported in the temperature-performance literature. There are two major types of problems, the first having been mentioned earlier in relation to Figure 6, refers to working memory (WM) being in short supply. But constraints of WM are eliminated when the task's requisite knowledge and skills are well rehearsed and residing in long term memory (LTM). Therefore the performance tests adopted in temperature-performance research should primarily place demands on WM rather than LTM; otherwise these tests may not be sensitive to the physical environment. Sensharma et al. [47] also emphasized that performance measures must be measurable and controllable, meaning they must be sensitive and

responsive to changes in the indoor environment. *Reading comprehension* and *proof reading* have commonly been used as cognitive performance tests in the indoor environment research domain (e.g. [108,109,110,111,147,263,270,271]), yet less common in other domains of performance research. Performance in these tests depends primarily on participants' intrinsic language skills which reside in their LTM rather than their cognitive skills located in WM. Consequently, when tested in various thermal environments, expert language users may experience little or no change of performance, whereas subjects with weaker language proficiency may be more adversely affected by thermal environmental stress. The final result may be predicted by the composition of the test sample—if there are high skill levels in the sample, performance may not be significantly affected, and vice versa.

Another potentially complicating issue is that a valid *productivity* measure may not be a valid *cognitive load/performance* measure for testing environmental impact. As discussed in Section 3, *productivity* involves many factors other than *performance* itself, thus a *productivity* measure may not be strictly appropriate for testing the effect of thermal environment on *performance*. Previous studies in call centres have adopted the average time per call or the number of calls handled during active working hours as productivity measures [85,272,273,274] for testing the impacts of thermal environments. Indeed, the average handling time is an important index for call centre productivity, but apart from the thermal environment, the handling time to serve a customer could also be influenced by many other factors including the nature and complexity of the queries, the standardized work process of call centres, the interaction between customers and service staff, personality and emotional state of the staff [73]. These factors almost certainly would have contributed to the significant changes in call centre productivity observed in those studies.

6. Implications of Different Models for Indoor Thermal Environmental Control and Building Energy Use

The range of indoor temperatures deemed acceptable by occupants has a strong bearing on building energy requirements because it constrains the geographic scope as well as the seasonal duration when passive design approaches are able to achieve acceptable indoor environments. Secondly, the indoor design temperature range indoors directly impacts energy required by active systems (HVAC) to achieve them. The most significant implication of the controversy over the inverted-U versus the extended-U models of thermal environmental effects on performance relates to the management of indoor environment of commercial premises [214,215]. The two models have diametrically opposed implications for the design and operation of indoor climate and associated energy requirements. The concept of a single-temperature optimum implied by the inverted-U model encourages facility managers to specify heating and cooling setpoints as close together as technology permits. In particular, the appearance of the single optimum model in *ASHRAE Handbook of Fundamentals* [27] (Figure 3) has contributed to the propagation of energy intensive control practices worldwide. Many countries such as Australia have gone as far as embedding tight thermal control clauses in commercial office space lease agreements [37,116] in the mistaken belief that the value of “lost” productivity resulting from temperature variations will grossly outweigh the energy costs of tight control (e.g. [46,51,71,111,275,276,277,278,279]). However, the analysis in the current paper casts doubt on simplistic dose-response relationships between temperature and cognitive performance, not to mention the more abstract construct of office productivity. The cost-benefit analysis is flawed on both sides of the ledger: the value of calculated productivity “losses” is questionable and the energy penalty of operating narrow control deadband are *non-trivial* because cooling systems are deployed intermittently to offset overheating and vice versa [214]. In effect, the widespread overcooling of commercial buildings in developed countries has incurred heavy energy, environmental and financial costs. Derrible and Reeder [30] has calculated the cost of over-cooling commercial buildings in US, 2012 to be 103,929 GWh for the energy cost, 57,125 kt CO₂ for the environmental cost, and US\$10 billion for the financial cost. Using World Bank data [280] to put these estimates into perspective, 103,929 GWh is slightly more than the total electricity consumption of Belgium in 2011 while 57,125 kt CO₂ is equivalent to the total greenhouse gas emissions by Norway in 2010, and ten billion US dollars represents the entire gross domestic product (GDP) of Mongolia (2012 value). In addition, a significant externality overlooked in this simplistic temperature-productivity calculus is the increment in greenhouse gas emissions associated with tight setpoint temperature deadband control strategies [263].

The extended-U model is accompanied by a theoretically coherent explanation of temperature effects on cognitive performance. Due to the wide range of intervening factors at play (as discussed in Section 5.1), occupants' cognitive performance remains in dynamic equilibrium under moderate levels of environmental stress, including thermal stress,

until adaptive resources or the “cognitive reserve” of the subject are depleted. As depicted in Figure 5, the central plateau area near optimal cognitive performance goes beyond the *comfort zone*, although the threshold may vary for different environment-, task- and performer-related factors. Implementation in facility management practice for indoor thermal environmental control, if performance is given priority, permits indoor temperatures to extend into the moderate thermal discomfort zone. But when thermal comfort and cognitive performance requirements are combined, it would be prudent for heating setpoints to align with the lower boundary of the comfort zone, and likewise cooling setpoint should align with the comfort zone’s upper boundary [38], or perhaps marginally further during electricity peak demand events [35]. Use of PCS hold promise for further extending the thermostat setpoint range beyond the comfort zone while still maintaining high levels of occupant thermal satisfaction [214,216,281,282].

In contrast to the waste of energy dictated by the inverted-U function, widening the thermostat setpoint range by implementing the extended-U model will lead to substantial savings in building HVAC energy. Previous researches have carried out simulation studies on the effect of wider HVAC thermostat deadband on the building energy consumption. Hoyt et al. [214] performed a dynamic thermal simulation study on the effects of wider thermostat setpoint ranges on annual HVAC energy requirements of typical, medium-sized office buildings in seven US climate zones. Compared with the baseline deadband range of 21.1–22.2 °C commonly practiced in many parts of the world, elevating the cooling setpoint from 22.2 °C to 25 °C while maintaining heating setpoint at 21.1 °C results in an average of 29% reduced cooling energy and 27% of total HVAC energy savings. Reducing the heating setpoint from 21.1 °C to 20 °C while maintaining the cooling setpoint at the default 22.2 °C yields an average of 34% heating energy savings. Adoption of PCS devices can further enlarge the deadband to 18.3–27.8 °C, which equates to 32%–73% of HVAC energy saving, depending on the climate zone. Similarly, Ghahramani et al. [283] studied the interrelationships between thermostat setpoints, deadbands and several other factors and concluded that HVAC deadband of 0, 1, 2, 4, 5, and 6 °C would result in an average energy savings of –70.0%, –34.9%, –13.7%, 9.6%, 16.4%, and 21.2%, respectively, compared to the baseline deadband of 3 °C. Daily optimal setpoint in the range of 22.5 ± 1 °C, 22.5 ± 2 °C, and 22.5 ± 3 °C would result in an average savings of 7.5%, 12.7%, and 16.4%, respectively, compared to the baseline setpoint of 22.5 °C.

7. Conclusions

For several decades the effect of thermal environment on performance has been a focus of research among indoor environmental scientists, but the work has been conducted and discussed in isolation from the broader domains of human performance science. In this paper we reviewed a collection of research publications, all specifically examining the effects of thermal environment on cognitive performance, but coming from a wide variety of disciplinary perspectives extending well beyond the usual indoor environmental sciences, including psychology, physiology, ergonomics, neuroscience, sports science, medical science, learning and instructional design, and human-technology interaction. Studies included static and transient thermal environmental exposures, extreme and moderate temperatures, and they reported inconsistent results ranging from cognitive performance decrements to null findings, and in some cases, even enhanced performance under moderate levels of thermal stress.

A plethora of confounding factors were identified as potential explanations of the inconsistencies. For example, Cognitive Load Theory contends that environment, task and performer are the three causal factors of cognitive load. The environment-related factors include intensity of thermal stress, duration of exposure and thermal transients. Performer-related factors include gender, age, skill level, acclimatization status, hydration status, emotion state, personality, to mention just a few. Task-related factors include task type and complexity. Two-way and three-way interactions between the environment, task and performer can also mediate cognitive load.

Two competing models linking thermal environment and cognitive performance emerged from our multidisciplinary literature review: the inverted-U relationship and the extended-U relationship. The inverted-U relationship is premised on Arousal Theory and features a single optimum temperature for maximal cognitive performance. The extended-U relationship, on the other hand, features a broad plateau of temperatures in which cognitive performance remains relatively unaffected. The boundaries of the performance plateau are characterised by progressive performance decrements as thermal environmental conditions become more extreme. Although the inverted-U relationship has held sway in the indoor environment research literature and practice, many researchers have criticized its overly simplistic

concept and methodologically flawed empirical bases. The unitary arousal notion is incongruent with known physiological and psychological effects, and emerging behavioural response data. It is implausible to characterise the human body as a simple linear transducer of environmentally imposed loads. The remarkable adaptability of our species enables us to absorb a range of externally imposed demands without any discernible decrement in performance.

Apart from confounding variables, methodological discrepancies between studies has no doubt lead to incompatible conceptual models: how to filter and report insensitive or dissociated data from three cognitive load measurement approaches can potentially cause confusion and controversy. Performance meta-analyses in the indoor environmental science literature have pooled results from diverse cognitive task types and complexity, each with their distinct performance decrement thresholds, and this has probably contributed to the glaring inconsistencies prevalent in the literature. Furthermore, the adoption of single-level, univariate regression analysis in several studies applied to repeated-measures with potential confounders may have also contributed to some of the false-positive evidence adduced in support of the inverted-U model. Finally, the performance measures used in some of the studies supplying evidence to support the inverted-U model are of questionable construct validity.

According to the extended-U model, indoor thermal environments can be controlled much less stringently than is currently practised. Building occupants have sufficient cognitive reserve and are also able to behaviourally adapt to moderate thermal environmental loads across, or even beyond the comfort zone, in order to protect performance without substantive increments in psychological or physiological demand. **Contrary to the inverted-U function that has incurred horrendous waste of energy, the extended-U relationship has huge potentials in building energy conservation.** Therefore, facility managers and building service engineers need to recognise that indoor temperatures spanning the full range of thermal acceptability (comfort zone) are serviceable instead of blindly pursuing a speciously defined single-temperature optimum.

8. Recommendations for Future Researches

Based on the analyses in this review, the following recommendations can be made for further research into the effects of moderate thermal environment on cognitive performance:

- 1) The effect of thermal environment on cognitive performance should not be used as a proxy for the effect of thermal environment on office productivity. The latter requires different measures that should be targeted in future studies.
- 2) Future studies should take potential confounding variables into consideration. As a minimum, the values of mediating factors should be reported for the purposes of future meta-analyses.
- 3) Standardized cognitive performance tests that place demands on working memory should be adopted; performance thresholds of different task types should be separately reported. Tasks with differing levels of complexity should be tested within the same task type.
- 4) Effects of thermal transients on cognitive performance warrants further exploration, particularly in workplace settings, as a strategy for preserving cognitive function while reducing peak electricity demand as well as overall HVAC energy requirements.
- 5) Further comparison and interpretation of results from diverse cognitive load measures are required before a robust, standardized methodology for studying thermal effects on cognitive performance can be established.

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