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Effects of heat stress on cognitive performance: the current state of knowledge

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This paper discusses the current state of knowledge on the effects of heat stress on cognitive performance. Although substantial research has been performed, it has proven difficult to describe the literature findings in a systematic manner. This is due to the large number of factors that come into play, such as task type, exposure duration, skill and acclimatization level of the individual and due to the absence of a concise theory on which experimental work can be based. However, two trends have been identified. First, heat stress affects cognitive performance differentially, depending on the type of cognitive task. Secondly, it appears that a relationship can be established between the effects of heat stress and deep body temperature. A number of exposure limits have been proposed during the last decades. These limits are summarized in this paper, with a special emphasis on the most recent one derived by Hancock and Vasmatzidis. This limit, which employs an attentional resource approach, defines exposure duration thresholds as parallel lines. Although this approach appears to be the most promising thus far, it is concluded that much remains to be understood before a limit becomes universally acceptable.

Key words: Heat stress, cognitive performance.

1. Introduction

The physiological responses of the human body to heat are well understood, modelled and documented. In contrast, despite a growing body of experimental studies in this area, the effects of heat stress on human cognitive abilities are less well understood. Current occupational heat stress exposure standards attempt to regulate exposure limits to hot environments based fundamentally on medical and physiological criteria[1,2]. However, focusing on the effects of the thermal environment on cognitive performance is very important for a number of compelling reasons. First, the World Health Organization defines good human health as comprising physical, *mental* (emphasis added by the authors) and social well-being[3]. A better understanding of cognitive performance under heat stress, a reflection of the state of human mental well being, can greatly help not only in defining occupational exposure limits in hot workplaces, but also in improving the quality of life in social and occupational settings. Secondly, a clear correlation has been found between heat stress and worker unsafe behaviour. In particular, Ramsey *et al.*[4] found that unsafe work behaviour in a products manufacturing plant and a foundry was minimal within the comfort range of 17–23°C WBGT, but unsafe acts increased significantly

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at higher temperatures up to 35°C WBGT. Therefore, to improve safety in the workplace, emphasis should be placed on assessing the cognitive and psychomotor abilities of the workers. Thirdly, the increased complexity in today's industrial and military systems has remarkably increased the level of mental workload imposed on the human operator[5], which, in turn, increases the propensity for human error. As prevention of human error has been a primary focus in modern human-technology interaction research, the issue of analysing cognitive performance under stress becomes of particular importance for determining workplace design parameters in occupational environments where a major portion of work done is of a cognitive nature. A classic example of such a complex work environment is air-traffic control. Although, to the authors' knowledge, there are no studies that have explicitly investigated air-traffic controlling performance under heat stress, the diminishing capability to perform simulated air-traffic controlling tasks in the presence of a number of stressors, has been clearly demonstrated[6]. For these reasons, various investigators[7–9] have advocated the establishment of worker exposure criteria to heat stress based primarily on cognitive rather than physiological performance considerations. As cognitive performance decrements are observed well before the physiological system reaches its tolerance limit, worker exposure in the heat should not be allowed if the level of the environmental stress compromises the cognitive abilities of the human operator. After all, in systems where one error can be fatal, it is clear that cognitive, not physiological assessment has the primacy.

2. Factors affecting performance in the heat

The overwhelming majority of work on the effects of heat stress on cognitive performance has been conducted in laboratory settings, where a number of participants have been exposed to a series of thermally stressful conditions, usually generated by specifying combinations of temperature and exposure duration. The lack of a systematic approach across these studies and the large number of thermal, experimental and participant variables involved has led various authors to report that a generalization on the effects of heat stress on mental performance is very difficult[10–14]. For example, although most studies have reported performance decrement in the heat, a number of studies have reported no effects of heat stress on mental performance[15–18], or even performance improvement upon initial exposure to heat[18–21]. It is important to identify the range of factors that are believed to have contributed to such a diverse pattern of findings. Task complexity appears to be the primary factor. Overall, it is shown that simple tasks such as reaction time and mental transformation tasks are less vulnerable to heat stress than more complex tasks such as vigilance, tracking and multiple tasks performed together[22–24]. The skill level of the individual is another such factor. Hancock[25] argued that 'operators with high skill levels on a task are better able to withstand the subsequent effects of heat stress' (p. 62). Hancock provided three potential explanations for this effect, the most plausible of which is the development of automatic processes in task performance. Thus, in highly overlearned tasks, stress does not have the opportunity to disrupt the link between stimulus and response. Duration of exposure may account for several contradictory results. In general, long exposures in stressful environments are expected to cause cognitive performance decrement. However, short exposures of up to 18 min have been associated with improved dual-task performance[21]. The acclimatization level of the participants has also been employed to account for lack of heat stress effects. However, the beneficial effects of acclimatization on psychological performance have been questioned[11]. Although not extensively investigated, another variable that merits a closer look is the relationship between gender and cognitive performance in the heat. For example, Wyon *et al.*[26] have reported that females can better withstand the negative effects of heat stress than males when short-term memory is required. There is also evidence that high incentives may neutralize the adverse effects of heat stress. In one study, Pepler[27] found that high incentive conditions in the form of target scores to be exceeded, and knowledge of results, together with verbal encouragement for better performance, produced better performance in the heat than the low incentive conditions of no knowledge of results and no verbal encouragement. However, these effects are probably transient[28] and it is doubtful if they would transfer to everyday work conditions. More recently, Vasmatzidis *et al.*[29] reported that providing knowledge of results in a multiple task scenario was associated with no performance decrement in hot environments up to 34°C WBGT. Finally, differences in experimental methodology may account for reported contradictory findings. One such case is the lack of heat stress effects on vigilance performance, a cognitively demanding type of task, for exposure to climates up to 90°F ET when participants were allowed to work in pairs and self-determine their work/rest periods[30]. Obviously, the intermittent nature of task performance enabled participants to superimpose rest periods during the heat exposure to an extent that nullified the adverse effect of heat stress on vigilance performance.

3. Effects of heat stress on cognitive performance: general trends

Despite this large number of variables that confound the effects of heat stress on cognitive performance, a number of investigators have attempted to explain these effects in a systematic way. Two main trends have emerged, which are not necessarily mutually exclusive. The first trend is that heat affects cognitive performance differentially, based on the type of cognitive task. An initial attempt to set a heat stress standard for unimpaired mental performance in the US[31] adopted Wing's[32] exponential curve, which defined a thermal tolerance limit without differentiating between task types. However, subsequent efforts to define exposure limits or outline the results of thermal stress on cognitive performance have made a clear distinction based on the type of task, with less attention demanding tasks being less vulnerable to heat stress effects than more attention demanding tasks[8,9,22,24,33,34]. A more elaborate discussion of the studies that support this interpretation is presented in the following section.

The second trend is the attempt to establish a relationship between deep body temperature and heat stress effects. With respect to vigilance performance, Hancock[35] argued that the key factor in predicting performance is the thermophysiological state of the performer. After a careful reinterpretation of the results of a large number of studies, Hancock proposed three basic thermal states of the human body, which define the efficiency of the operator exposed to hot climates:

(1) A dynamic state in which the imposed thermal load causes the deep body temperature of the observer to increase away from a normative comfort level. In this state, heat storage in the body accumulates over time and performance breakdown will soon be observed.

(2) A hyperthermic state characterized by a constant elevated internal body temperature. Most of the available evidence suggests that watchkeeping performance improves in this state.

(3) A state in which the external thermal load is not intense enough to cause an elevation of the observer's deep body temperature. In this state, vigilance performance remains essentially unaffected. In general, the upper limit of environmental exposure which induces no change in deep body temperature of the individual is 29.4°C (85°F). This heat stress level coincides with Lind's upper limit[36] of the 'prescriptive zone' and the upper limit of the zone of 'thermal equilibration'[37].

Interestingly, no similar attempts have been made to relate the thermophysiological state of the performer with other types of cognitive tasks, such as simple mental tasks, dual tasks and more complex cognitive tasks. It has been argued, however[8,9,24], that different rates of rise of the deep body temperature reflect the limit for performance degradation for different types of tasks. In particular, the rates of deep body temperature rise of 0.055, 0.22, 0.88 and 1.33°C per hour of exposure signify performance decrement thresholds for vigilance, dual-task, tracking and simple mental performance, respectively. Such dynamic rises are caused by exposures to thermal stress conditions where heat accumulation in the body over time disrupts thermal equilibrium and, therefore, they reflect changes that can not be compensated for. In addition, certain studies of controlled hyperthermia by means of regulating the temperature in liquid conditioned suits have indicated that, above the critical body core temperature of 37.5°C, heating causes significantly worse performance than cooling. In particular, these studies recorded performance as the deep body temperature was rising and then falling between the pre-determined limits of 37.0–37.6°C[38], 37.9–38.5°C[39,40] and 38.2–38.9°C[41]. Consequently, those investigators concluded that it is the direction of movement and not the absolute level of the internal temperature alone that determines quality of performance.

4. Heat stress exposure limits: the current state

In an early attempt to define limits for unimpaired mental performance in the heat, NIOSH[31] adopted Wing's[32] curvilinear description (see figure 1). However, these limits are no longer considered to be valid for a number of reasons. Wing's limits were established using the effective temperature (ET) scale as the metric of the environmental thermal load. NIOSH, however, simply replaced the ET scale with the Wet Bulb Globe Temperature (WBGT) scale, thus implying equivalence between the two scales, an approach that is completely unfounded. Hancock[23] re-evaluated Wing's threshold and provided a revision of these tolerance limits based on correction of factual errors and suspect interpretations. The revised curve, which was still curvilinear, was less conservative and suggests that simple mental impairment occurs just before the point of physiological collapse to heat.

Following this early NIOSH attempt, a number of investigators have proposed revised exposure limits. It is interesting to note that all point to some form of task differentiation. Grether[22] was the first to suggest dividing experimental findings according to task type. He described five types of cognitive tasks: time estimation, reaction time, tracking, vigilance and monitoring, and cognitive and other tasks. Grether suggested that time estimation and reaction time is sped up upon exposure to the heat due to an increased speed of neural conduction associated with elevated body temperature. With respect to the rest of the tasks, Grether suggested 80°F ET to be the environmental temperature for optimum performance for vigilance tasks, and 85°F ET as the temperature for optimum performance for the rest of the task

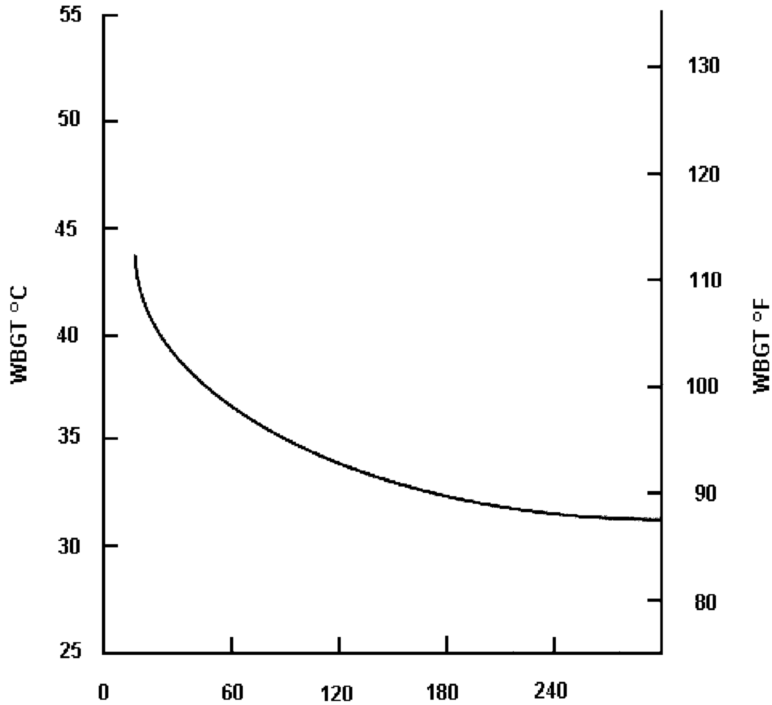

Figure 1. Upper tolerance limits for unimpaired mental performance (from NIOSH[31]).

categories. This latter limit coincides with Lind's upper limit of the 'prescriptive zone'. Although these limits did not receive immediate acceptance, they do point to the fact that simple tasks are less vulnerable to heat stress than more complex tasks, and that vigilance and monitoring performance is the most sensitive type of performance to the adverse effects of heat stress.

A more systematic attempt to outline performance decrements under conditions of high thermal stress was provided by Ramsey and Morrissey[33]. They introduced the concept of 'isodecrement' curves, that is curves specifying temperature and time combinations for which a certain probability for performance decrement is expected. Isodecrement curves for five types of cognitive performance were developed: mental (e.g. coding, multiplication/writing, mental arithmetic), tracking, reaction time, vigilance and complex task performance. These types were eventually combined into two sets of curves: one for mental and reaction time performance and one for the rest of the tasks. Figures 2 and 3 illustrate these isodecrement curves for mental performance tasks and tracking tasks, respectively. The curves, which were developed by constructing performance prediction equations based on a large number of heat stress studies, emphasize two points. First, task differentiation is necessary for synthesizing the effects of heat stress on cognitive performance. Secondly, the adverse effects of heat stress are manifested in a gradual manner and can potentially be represented by a probability for performance impairment. This notion deserves further investigation and seems amenable to the use of a fuzzy logic approach[42,43].

More recently, Ramsey and Kwon[34] summarized the effects of heat stress on cognitive performance by examining the results from more than 150 studies. In keeping with their previous task categorization[33], they distinguished between '(1)

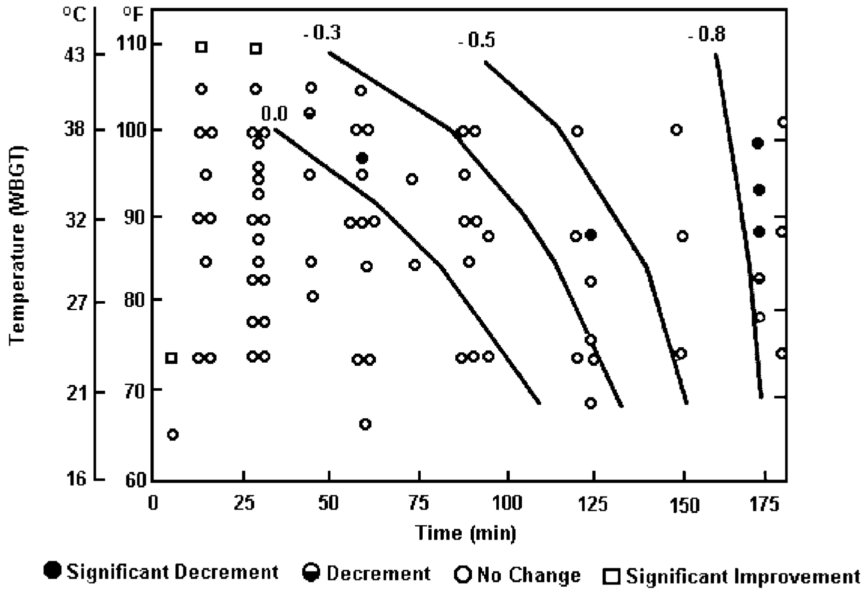

Figure 2. Isodecrement curves for mental performance tasks. Numbers in the graph represent levels of likelihood for unimpaired task performance, ranging from 0.0 (no change in task performance) to 1.0 (definite significant performance decrement). (Reprinted from Ramsey JD, Morrissey SJ. Isodecrement curves for task performance in hot environments, *Appl Ergon* 1978; 9.2: 66–72, Copyright 1978, with permission from Elsevier Science.)

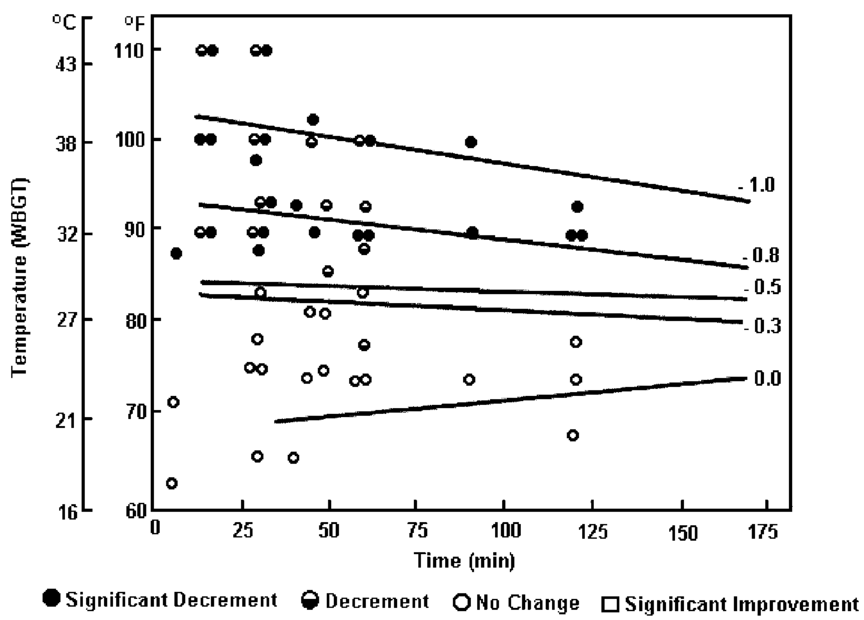

Figure 3. Isodecrement curves for tracking tasks. Numbers in the graph represent levels of likelihood for unimpaired task performance, ranging from 0.0 (no change in task performance), to 1.0 (definite significant performance decrement). (Reprinted from Ramsey JD, Morrissey SJ. Isodecrement curves for task performance in hot environments, *Appl Ergon* 1978; 9.2: 66–72, Copyright 1978, with permission from Elsevier Science.)

mental, very simple, perceptual motor, reaction time, etc.' and '(2) other perceptual motor tasks, including tracking, vigilance, complex/dual, etc.' (p. 247). Within these categories, they established whether the studies reported a statistically significant performance decrement or enhancement, a non-statistically significant partial decrement or no change in performance. Their results are shown in figures 4 and 5 for mental or simple tasks and for perceptual motor tasks, respectively. Ramsey and Kwon confirmed Hancock's[23] conclusion that simple mental tasks show little, if any, decrement in the heat, and are frequently enhanced during brief exposures of up to 30 min. However, tasks in the second category (perceptual motor tasks) show the onset of statistically significant decrements in the range between 30–33°C WBGT, regardless of the duration of exposure. As Ramsey and Kwon pointed out, this range coincides with the recommended heat stress alert and exposure limits adopted by NIOSH[1] and ISO[44] for workers performing sedentary or light work, which were established on the premise that the worker's internal body temperature should not exceed the threshold value of 38°C.

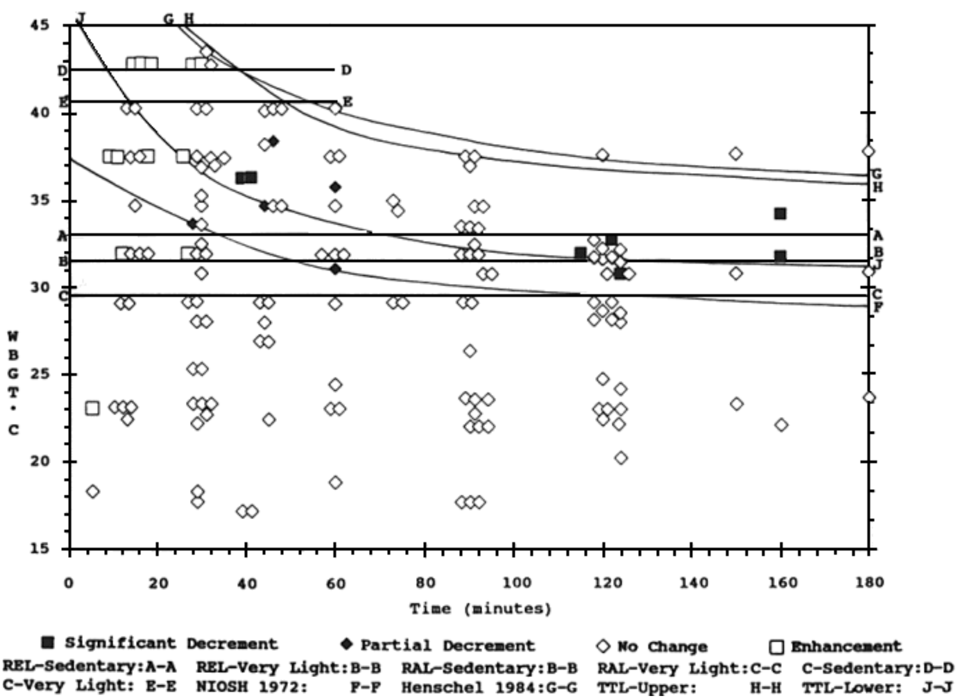

Figure 4. Mental or simple task performance in the heat and proposed temperature–time limits for human responses. REL (Recommended Exposure Limit) applies to heat acclimatized workers. RAL (Recommended Alert Limit) applies to heat unacclimatized workers[1]. Curves A–A, B–B and C–C are limits for 1-h time-weighted average exposure. Curves D–D and E–E are the NIOSH ceiling limits for sedentary and very light work, respectively[1]. Curve F–F is the NIOSH limit[31]. Curve G–G was derived by Ramsey and Kwon[34]. Curve H–H represents the upper thermal tolerance limits for unimpaired neuromuscular performance and curve J–J represents the time–temperature conditions where no change in deep body temperature is expected for sedentary workers, as specified by Hancock and Vercruyssen[37]. (Reprinted from Ramsey JD, Kwon YG. Recommended alert limits for perceptual motor loss in hot environments. *Int J Ind Ergon* 1992; 9: 245–57, Copyright 1992, with permission from Elsevier Science.)

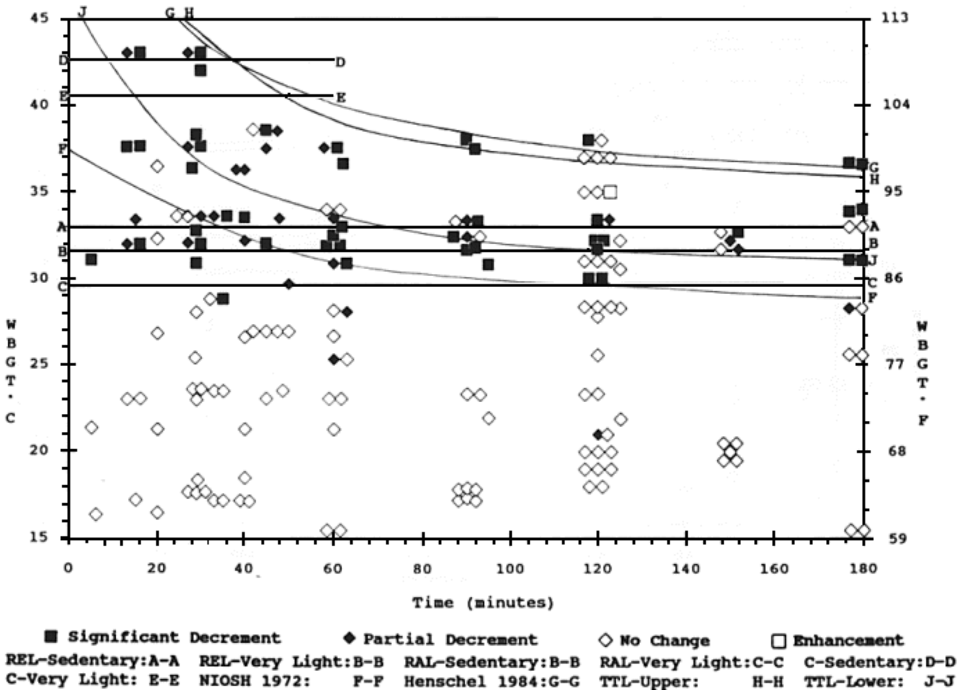

Figure 5. Perceptual motor task performance in the heat and proposed temperature–time limits for human responses. REL (Recommended Exposure Limit) applies to heat acclimatized workers. RAL (Recommended Alert Limit) applies to heat unacclimatized workers[1]. Curves A–A, B–B and C–C are limits for 1-h time-weighted average exposure. Curves D–D and E–E are the NIOSH ceiling limits for sedentary and very light work, respectively[1]. Curve F–F is the NIOSH limit[31]. Curve G–G was derived by Ramsey and Kwon[34]. Curve H–H represents the upper thermal tolerance limits for unimpaired neuromuscular performance and curve J–J represents the time–temperature conditions where no change in deep body temperature is expected for sedentary workers, as specified by Hancock and Vercruyssen[37]. (Reprinted from Ramsey JD, Kwon YG. Recommended alert limits for perceptual motor loss in hot environments. *Int J Ind Ergon* 1992; 9: 245–57, Copyright 1992, with permission from Elsevier Science.)

In their work, Ramsey and Kwon noted that earlier reviews, namely that of Grether[22] and Kobrick and Fine[10], failed to present a common denominator for interpreting the results of heat stress effects on various types of cognitive tasks. Such a common denominator, however, has been provided by Hancock[24], who asserted that it is the rate of change of the deep body temperature that signifies the onset of cognitive performance decrement in the heat. Specifically, following a careful and detailed evaluation of a number of studies, Hancock argued that the dynamic increases (increases beyond any thermally stable state that can not be compensated for) in deep body temperature of 0.22°C (0.4°F), 0.88°C (1.6°F) and 1.33°C (2.4°F) per hour of exposure can be associated with the onset of performance decrement for dual tasks, tracking tasks and simple mental tasks, respectively. These conditions, in a temperature-exposure time domain, are described by the curves shown in figure 6. The upper curve in figure 6 reflects the physiological tolerance limit as obtained by Gorodinskii *et al.*[45] and represents a dynamic rise in deep body temperature of 1.67°C (3°F). Figure 6 is a synthesis of the heat stress studies conducted by

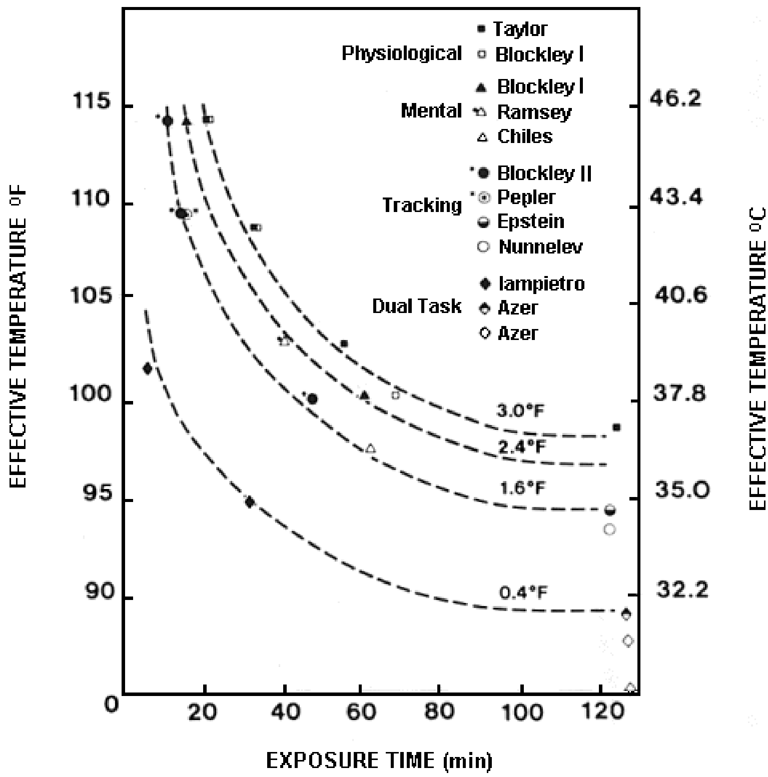

Figure 6. Heat stress limits for unimpaired mental performance based on a number of studies. Superimposed are dashed lines representative of prescribed rises in deep body temperature which accrue from the Effective Temperature–Exposure Time combinations described by the figure[24]. (Reprinted with permission.)

Taylor[46], Blockley and Lyman[47] (designated as Blockley I in figure 6), Ramsey *et al.*[48], Chiles[16], Blockley and Lyman[49] (designated as Blockley II in figure 6), Pepler[50], Epstein *et al.*[51], Nunneley *et al.*[18], Iampietro *et al.*[52] and Azer *et al.*[53]. In figure 6, each of these studies is identified by the name of the first author of the respective study. With respect to simple mental tasks, Hancock's and Ramsey and Kwon's findings are in agreement in that they both indicate that performance decrement for this type of performance is observed just before the limit for physiological collapse.

Staying in line with this earlier limit derivation, and adding to it a limit for vigilance performance represented by a dynamic rise in deep body temperature of 0.055°C (1°F) per hour of exposure, Hancock and Vasmatzidis[8,9] presented a new framework of setting performance limits in the heat, which are presented in figures 7 and 8. In this new framework, exposure limits for different types of cognitive tasks can be described as parallel lines of the form:

$$ET = a - 4.094 \log_e T \quad (1)$$

or

$$WBGT = a - 5.435 \log_e T \quad (2)$$

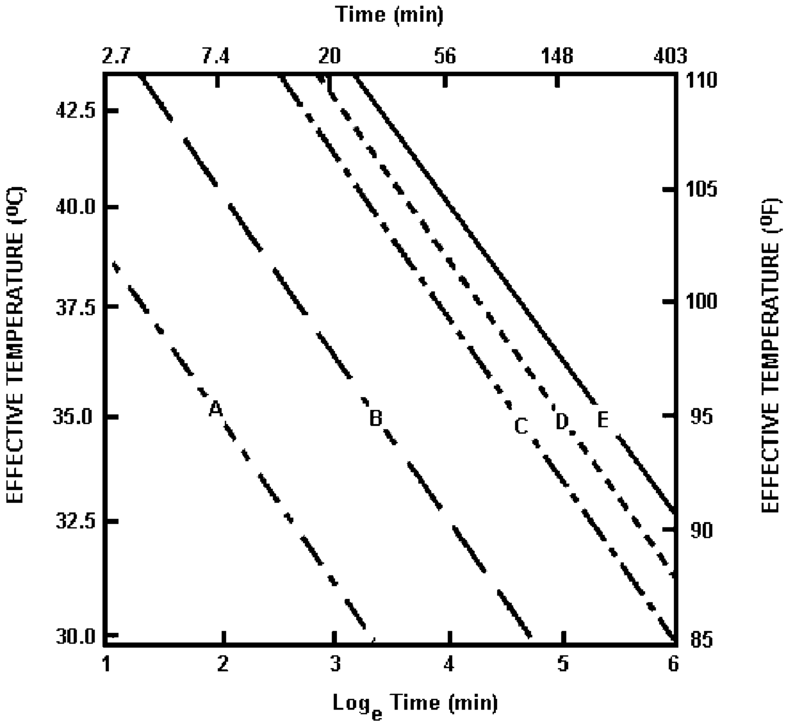

Figure 7. Human performance limits in (ET)/Log$_e$(Time) Cartesian space for vigilance performance (line A), dual-task performance (line B), tracking performance (line C), simple mental performance (line D). Line E represents the physiological tolerance limit[8,9].

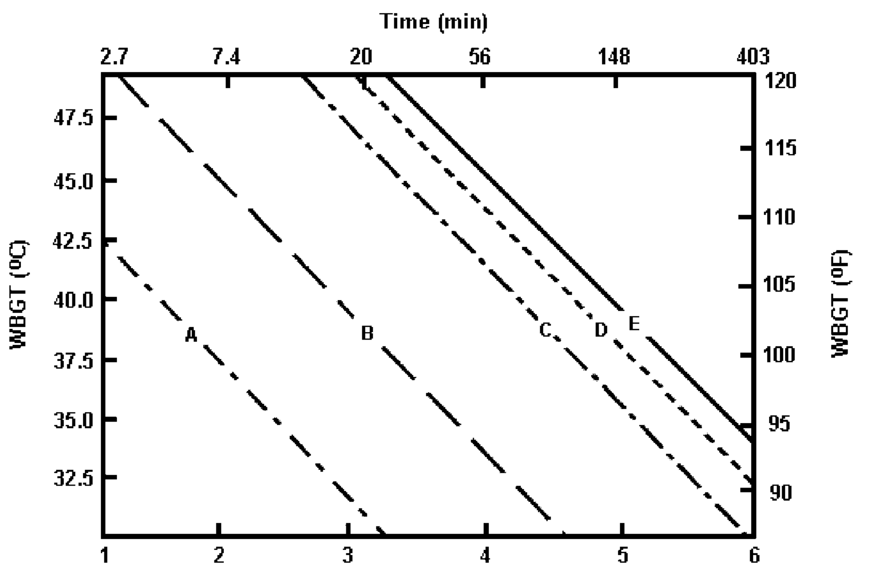

Figure 8. Human performance limits in (WBGT)/Log$_e$(Time) Cartesian space for vigilance performance (line A), dual-task performance (line B), tracking performance (line C), simple mental performance (line D). Line E represents the physiological tolerance limit[8,9].

Table 1. Intercept values and rise in deep body temperature for the limits proposed by Hancock and Vasmatzidis[8,9].

Curve	Task type	Empirical intercept for ET limits	Tolerance adjusted intercept for ET limits	Empirical intercept for WBGT limits	Tolerance adjusted intercept for WBGT limits	Dynamic rise in deep body temperature (°C)
A	Vigilance	42.82	41.00	48.02	45.00	0.055
B	Dual-task	48.59	47.00	55.68	54.00	0.22
C	Tracking	53.96	53.00	63.11	62.50	0.88
D	Simple mental	55.81	54.00	65.33	64.00	1.33
E	Physiological tolerance	57.06	55.00	66.56	65.00	1.67

where *ET* is the effective temperature, *WBGT* is the Wet Bulb Globe temperature and *T* the exposure duration in minutes. As these limits indicate, vigilance performance is the most sensitive to heat stress, followed by dual task performance, tracking performance and simple mental performance, which, once again, is expected to suffer just before the threshold for physiological collapse is reached. The intercept values *a* in the above equations reflect the attentional involvement required for each task category plotted. The higher the value of parameter *a*, the higher the respective performance limit (and the associated dynamic rise in deep body temperature) and the lesser the attentional demand placed on an individual by the task. Hancock and Vasmatzidis provided two sets of intercept values, one based on empirical data and one representing a conservative adjustment so that the limits can be used as acceptable tolerance standards. Thus, the tolerance adjusted intercepts incorporate a 'time safety factor', which in real-world occupational settings reflects the time period needed to exit the heat and/or to help a co-worker. Both sets of intercept values for equations (1) and (2) are presented in table 1.

As the authors pointed out, the linearity of their limits is not the only significant feature of the illustration. Each threshold is associated with a different rise in deep body temperature (also shown in table 1), which the authors used as the basis for converting the limits from the ET—exposure time domain to the WBGT—exposure time domain, through the relationship provided by Jensen and Heims[54]. Such a conversion was necessary as WBGT is the preferred index in virtually all current heat stress exposure standards[55].

It should be noted that the overwhelming majority of studies on the effects of heat on mental performance did not use WBGT as the metric of the impinging environmental stress, but rather reported ET values. WBGT is designed to include the impact of radiant heat on the intensity of the environmental thermal load, in addition to the effects of air temperature, humidity and air velocity. The ET scale is a subjective scale of equal comfort that was developed without considering the impact of radiant heat. The effect of radiant heat was introduced later and led to the development of the Corrected Effective Temperature scale (CET). Thus, it is imperative that a method be adopted to convert reported ET levels to respective WBGT levels. Ramsey and Kwon[34] used the nomograms for ET–CET to convert into WBGT units[56]. For their analysis, an estimate of the environmental conditions was made for studies which did not report sufficient information for the conversion to take place.

5. Effects of heat stress on mental performance: theoretical considerations

The lack of a systematic approach in investigating the effects of heat stress on cognitive performance is, to a large extent, due to the lack of a concise theory on which experimental results can be based[12]. Although several psychological models on the effects of stress (and therefore heat stress) have been developed[57–60], arousal theory has been used most extensively in the literature to explain the effects of heat stress on cognitive performance.

Arousal theory[61–63] postulates an inverted–U relationship between human performance and the arousal level of the performer (see figure 9), a relationship also known as the Yerkes-Dodson law. As arousal increases toward an optimal level, the quality of performance improves. Beyond that optimal level, at which performance is best, performance gradually declines as arousal continues to increase. With respect to the effects of heat on performance, many investigators have assumed the same inverted-U relationship, and attempted to associate the level of arousal with the intensity of the environmental thermal load[21,64–66]. In summary, as the environmental temperature (or body core temperature) rises, the arousal level of the performer increases, which in turn causes performance to improve. At some critical point of ambient (or core) temperature, no further improvement is possible and performance decreases with increasing heat (and arousal). Provins[67] was the first to synthesize this relationship into a formal hypothesis. In addition, he encompassed the dimension of task complexity as one of the arousal determinants. Thus, according to Provins, more arousing tasks (e.g. dual tasks) present performance decrements at lower temperatures than less arousing tasks (e.g. simple mental tasks).

Arousal theory has undergone a great deal of criticism, and its validity and robustness have been questioned. For example, Hancock[68] argued among other things that the theory is highly descriptive but its predictive power is very limited. The inverted-U relationship has rarely been quantified in the literature and, in general, the function moves freely to any location in the Cartesian space in a post-hoc manner to fit the available data set. For this same reason, it has proved impossible to use arousal theory to guide experimental work in a predictive manner.

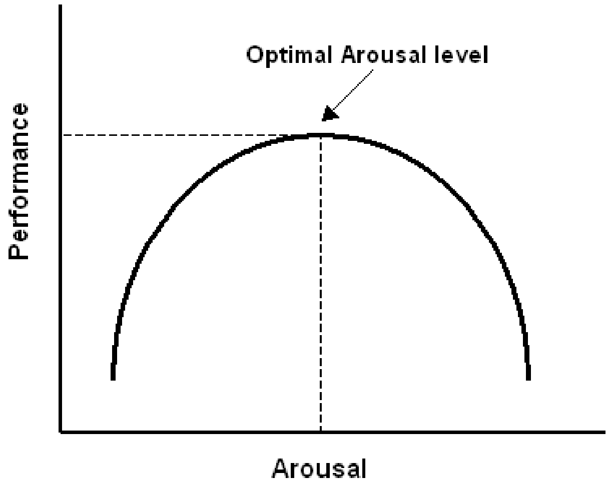

Figure 9. The inverted-U relationship between arousal and task performance.

A more recent model is the Maximal Adaptability Model[69], which assumes that heat exerts its detrimental effects on performance by competing for and eventually draining attentional resources[70]. Hancock and Vasmatzidis[8,9] used this model as the theoretical basis for their limits. Briefly, as shown in figure 10, input stress can vary from a low extreme (hypostress) to a high extreme (hyperstress). In the middle of this continuum is the normative zone, which requires no compensatory action on the part of the individual. Surrounding the normative zone is the zone of comfort wherein cognitive adjustments to task demands are easily accomplished. As a result, performance within the comfort zone is at near-optimal level. As the level of environmental stress increases (by increasing exposure duration or the intensity level of the stressor or both), attentional resources are progressively drained. Initially, the remaining resources are efficiently used by the individual via adaptive strategies such as attentional focus[71], with the net result being no performance decrement, or even performance enhancement. This behaviour is a refection of psychological adaptability and is noticed within the psychological zone of maximal adaptability of figure 10. At higher levels of stress, depletion of cognitive resources results in a progressive decline of performance efficiency, as indicated by the dashed line comprising the boundary of the psychological zone of maximal adaptability. For example, in a recent study, Chase *et al.*[72] reported poor dual-task performance at 30 and 35°C WBGT due to the inability of the participants to successfully allocate attention to the tasks of the study. At this point (beyond the boundary), physiological stability is also disturbed. Further increases in stress intensity move the body outside the zone of homeostasis (physiological zone of maximal adaptability) into life-threatening circumstances (heat stroke for example).

With respect to heat stress, the maximal adaptability model establishes a relationship between the physiological and psychological aspects of work in the heat. As it assumes attentional resource depletion to be the mechanism for the debilitating

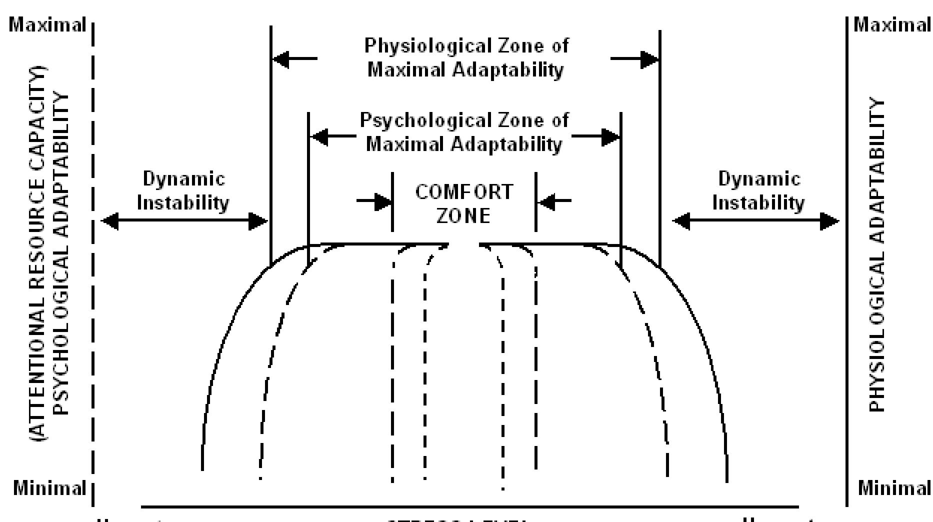

Figure 10. The maximal adaptability model. (Reprinted with permission from *Hum Factors* 1989; 31(5). Copyright 1989 by the Human Factors and Ergonomics Society. All rights reserved.)

effects of heat stress, it also establishes a relationship between the magnitude of such depletion (expressed in terms of dynamic body core temperature increase) and the onset of performance decrement. This relationship is represented by the limits proposed by Hancock and Vasmatzidis[8,9] which were summarized in table 1. At present, this structure provides the most comprehensive description and theory, as it pertains to thermal stress and its general principles can be applied to understanding the action of all forms of occupational stress.

6. Concluding remarks

Over the years, a number of investigators have attempted to evaluate and present the results of heat stress effects on cognitive performance in an organized manner. It appears that due to the large number of thermal, experimental and participant variables involved, such an attempt is not an easy task. With respect to performance thresholds, the general trend is to define them as a function of the type of cognitive task. Ramsey and Kwon[34] reported such a differentiation, with very simple mental and perceptual motor tasks comprising one category, and more complex perceptual motor tasks comprising a second category. They concluded that simple tasks do not exhibit impairment due to heat stress up to thermal intensity levels close to those signifying imminent physiological collapse. The more complex tasks show signs of performance decrement in the range of 30–33°C WBGT. It is interesting to note that Ramsey and Kwon stopped short of advocating utilization of their limits as stress standards. They cited two reasons for this: first, they indicated that significant decrement in a laboratory setting does not necessarily imply loss of the ability to perform a cognitively demanding task in practical situations. Secondly, there are a large number of confounding variables (some of which have been discussed here) that can affect task performance and, therefore, interact with the effects of heat.

Hancock and Vasmatzidis[8,9], on the other hand, did suggest that their limits could be used as tolerance standards to prevent performance decrement under thermal stress. They specifically differentiated among vigilance, dual-task, tracking and simple mental performance, and associated decrements for these types of performance with certain levels of dynamic rise in deep body temperature. They argued that the more cognitively demanding the nature of the task, the lower the limit for unimpaired performance. However, they adopted a conservative approach before suggesting potential use of their limits as standards. In their mathematical formulation that describes the temperature-exposure duration combination that delimits the onset of performance decrement, they provided two sets of intercept values with the temperature axis: one that was empirically derived and one which included an inherent safety factor. Then, they recommended the lower intercepts as appropriate for a heat stress standard.

Ramsey and Kwon were absolutely right to point to the need to demonstrate the generalizability of the vast volume of experimental work to practical situations. As experimental studies varied in many aspects, and typically utilized young, healthy subjects, such a generalization is indeed very difficult. However, understanding the mechanism through which heat stress exerts its effects offers an avenue through which such a generalization might be possible. Hancock and Vasmatzidis do offer such a mechanism: the *dynamic* increase in deep body temperature. Therefore, their approach holds promise as current work has shifted from experimental endeavours to understanding the effects of heat stress on cognitive performance. It is hoped that such an understanding will lead to the establishment of universal heat stress standards for cognitive performance.

One final area worthy of more investigation is that of the appropriate heat stress index for measuring the intensity of heat stress in relation to cognitive work. The majority of heat stress studies have utilized effective temperature (ET), which is a subjective scale. In contrast, current heat stress standards have adopted the Wet Bulb Globe Temperature. Although there are a number of methods that can be used to convert ET to WBGT, there is a major issue associated with such conversions, beyond the small error of the associated mathematical relationships. The WBGT index was developed to include radiant heat as a contributor to the overall intensity of heat stress. However, there is no reason to believe that there is a cognitive performance equivalence between the WBGT value obtained by translation of the respective ET environments and the same WBGT value obtained by directly specifying the intensity of the radiant heat stress element. In other words, the impact of radiant heat on cognitive performance has not been investigated. Furthermore, the issue of using WBGT in setting heat stress limits for cognitive performance is further complicated by the potentially differential effect on cognitive performance of different dry-bulb/relative humidity combinations, for the same value of WBGT. For example, in a recent study, Vasmatzidis *et al.*[29] found that, at 34°C WBGT, the high level of relative humidity (70%) was more detrimental to time-sharing performance than the lower level of 30% relative humidity.

Each of these observations suggests that the present state of knowledge is still at a general level and factors such as worker age, gender, level of experience, motivation and training can all exert important effects which need to be better understood. Furthermore, how aspects of the environment such as local radiant heat sources affect cognitive, as opposed to physiological functioning is almost completely unknown. Standards essentially represent the present state of knowledge and are, thus, correct in adopting conservative values, since it has been found with progressive research that human performance is more often vulnerable rather than insensitive to even moderate levels of stress. In the future, it may well be that standards *themselves* are dynamic, as one is able to use technology to track an individual in any surround and assess the state of response capacity on-line. While such personalization is to be embraced, it can only succeed when based on sound experimental findings. Like many forms of occupational stress, there is much to be understood about the impact of thermal environment on cognitive performance.

References

1. National Institute for Occupational Safety And Health (NIOSH). *Occupational exposure to hot environments: Revised criter*ia, Washington DC: US Government Printing Office, 1986; Publication No. 86–113.
2. International Standards Organization (ISO). *Hot environments—Analytical determination and interpretation of thermal stress using calculation of required sweat rate*, Geneva: ISO, 1989; Standard , and 7933.
3. Preamble to the Constitution of the World Health Organization as adopted by the International Health Conference, New York, 19–22 June 1946; signed on 22 July 1946 by the representatives of 61 States (Official Records of the World Health Organization, no 2, p. 100) and entered into force on 7 April 1848.
4. Ramsey JD, Burford CL, Beshir MY, Jensen, RC. Effects of workplace thermal conditions on safe work behavior. *J Safety Res* 1983; 14: 105–14.
5. Hancock PA, Meshkati N, eds. *Human Mental Workload*, Amsterdam: North Holland, 1988.

6. Issued by funding/sponsoring agency: Gilliland K, Schlegel RE, Nesthus TE. Workshift and Antihistamine effects on task performance. Final Report. Oklahoma City (OK): Federal Aviation Administration, Civil Aeromedical Institute; 1996 Mar. Report No.: DTFA-02-93-D-93088.
7. Hancock PA. Performance criteria as exposure limits in heat stress. In: Asfour SS, ed., *Trends in Ergonomics/Human Factors IV*, Amsterdam: Elsevier Science, 1987; 333–40.
8. Hancock PA, Vasmatzidis I. Human occupational and performance limits under stress: the thermal environment as a prototypical example. *Ergonomics* 1998; 4: 1169–91.
9. Hancock PA, Vasmatzidis I. On the behavioral basis for stress exposure limits: the foundational case of thermal stress. In: Karwowski W, Marras WS, eds, *The Occupational Ergonomics Handbook*, Boca Raton, FL: CRC Press, 2000; 1707–39.
10. Kobrick JL, Fine BJ. Climate and human performance. In: Oborne DJ, Gruneberg MM, eds, *The Physical Environment at Work*, Chichester: Wiley, 1983; 69–107.
11. Enander AE. Effects of thermal stress on human performance. *Scand J Work Environ Health* 1989; 15 (Suppl 1): 27–33.
12. Enander AE, Hygge S. Thermal stress and human performance. *Scand J Work Environ Health* 1990; 16 (Suppl 1): 44–50.
13. Ramsey JD. Working safely in hot environments. In: Das B, ed., *Advances in Industrial Ergonomics and Safety II*, London: Taylor & Francis, 1990; 889–96.
14. Ramsey JD. Task performance in heat: a review. *Ergonomics* 1995; 38: 154–65.
15. Bell CR, Provins KA, Hiorns RW. Visual and auditory vigilance during exposure to hot and humid conditions. *Ergonomics* 1964; 7: 279–88.
16. Chiles WD. Effects of elevated temperature on performance of a complex mental task. *Ergonomics* 1958; 2: 89–96.
17. Colquhoun WP. Effects of raised ambient temperature and event rate on vigilance performance. *Aerospace Med* 1969; 40: 413–7.
18. Nunneley SA, Dowd PJ, Myhre LG, Stribley RF, McNee RC. Tracking-task performance during heat stress simulating cockpit conditions in high-performance aircraft. *Ergonomics* 1979; 22: 549–55.
19. Colquhoun WP, Goldman RF. Vigilance under induced hyperthermia. *Ergonomics* 1972; 15: 621–32.
20. Lovingood BW, Blyth CS, Peacock WH, Lindsay RB. Effects of d-amphetamine sulfate, caffeine and high temperature on human performance. *Res Quart* 1967; 38: 64–71.
21. Poulton EC, Kerslake MB. Initial stimulating effect of warmth upon perceptual efficiency. *Aerospace Med* 1965; 36: 29–32.
22. Grether WF. Human performance at elevated environmental temperatures. *Aerospace Med* 1973; 44: 747–55.
23. Hancock PA. Heat stress impairment of mental performance: a revision of tolerance limits. *Aviat Space Environ Med* 1981; 52: 778–84.
24. Hancock PA. Task categorizations and the limits of human performance in extreme heat. *Aviat Space Environ Med* 1982; 53: 778–84.
25. Hancock PA. The effect of skill on performance under an environmental stressor. *Aviat Space Environ Med* 1986; 57: 59–64.
26. Wyon DP, Andersen I, Lundqvist GR. The effects of moderate heat stress on mental performance. *Scand J Work Environ Health* 1979; 5: 352–61.
27. Pepler RD. Warmth and performance: an investigation in the tropics. *Ergonomics* 1958; 2: 63–88.
28. Konz S. *Work Design: Industrial Ergonomics*, 2^{nd} edn, New York: John Wiley & Sons, 1983.
29. Vasmatzidis I, Schlegel RE, Hancock PA. An investigation of heat stress effects on time-sharing performance. *Ergonomics* 2002; 45: 218–39.
30. Ramsey JD, Halcomb CG, Mortagy AK. Self-determined work/rest cycles in hot environments. *Int J Prod Res* 1974; 12: 623–31.
31. National Institute for Occupational Safety and Health (NIOSH). *Criteria for a Recommended Standard—Occupational Exposure to Hot Environments*, Washington DC: US Government Printing Office, 1972; Publication No. 72-10269.
32. Wing JF. Upper thermal tolerance limits for unimpaired mental performance. *Aerospace Med* 1965; 36: 960–4.

33. Ramsey JD, Morrissey SJ. Isodecrement curves for task performance in hot environments. *Appl Ergon* 1978; 9: 66–72.
34. Ramsey JD, Kwon G. Recommended alert limits for perceptual motor loss in hot environments. *Int J Ind Ergon* 1992; 9: 245–57.
35. Hancock PA. Sustained attention under thermal stress. *Psychol Bull* 1986; 99: 263–81.
36. Lind AR. A physiological criterion for setting thermal environmental limits for every day work. *J Appl Physiol* 1963; 18: 51–56.
37. Hancock PA, Vercruyssen M. Limits of behavioral efficiency for workers in heat stress. *Int J Ind Ergon* 1988; 3: 149–58.
38. Gibson TM, Allan JR. Effect on performance of cycling deep body temperature between 37.0 and 37.6C. *Aviat Space Environ Med* 1979; 59: 935–8.
39. Allan JR, Gibson TM. Separation of the effects of raised skin and core temperature on performance of a pursuit rotor task. *Aviat Space Environ Med* 1979; 50: 678–82.
40. Gibson TM, Allan JR, Lawson CJ, Green RG. Effect of induced cyclic changes of deep body temperature on performance of a flight simulator. *Aviat Space Environ Med* 1980; 51: 356–60.
41. Allan JR, Gibson TM, Green RG. Effect of induced cyclic changes of deep body temperature on task performances. *Aviat Space Environ Med* 1979; 50: 585–9.
42. Zadeh LA. Fuzzy sets. *Inform Con* 1965; 8: 338–53.
43. Parasuraman R, Masalonis AJ, Hancock PA. Fuzzy signal detection. *Hum Factors* 2000; 42: 636–59.
44. International Standards Organization (ISO). *Hot Environments—Estimation of heat stress on working man based on the WBGT index*, Geneva: ISO, 1982; Standard #7243.
45. Gorodinskii SM, Bavro GV, Perfilova EM, Pletenskii YG, Salivon SG. Heat stress dynamics and limits of heat tolerance in man. *Environ Space Sci* 1968; 2: 66–73.
46. Taylor CL. Committee on Aviation Medicine, Interim Report, NRC, Washington DC, 1948.
47. Blockley WV, Lyman JH. Studies of human tolerance for extreme heat: III. Mental performance under heat stress as indicated by addition and number checking tests, USAF Technical Report 6022, Ohio: Wright Paterson AFB, 1950.
48. Ramsey JD, Dayal D, Ghahramani B. Heat stress limits for the sedentary worker. *Am Ind Hyg Ass J* 1975; 36: 259–65.
49. Blockley WV, Lyman JH. Studies of human tolerance for extreme heat: IV. Psychomotor performance of pilots as indicated by a task simulating aircraft instrument flight. USAF Technical Report 6521, Ohio: Wright Paterson AFB, 1951.
50. Pepler RD. Extreme warmth and sensorimotor coordination. *J App Physiol* 1959; 14: 383–6.
51. Epstein Y, Keren G, Moisseiev J, Gasko O, Yachin S. Psychomotor deterioration during exposure to heat. *Aviat Space Environ Med* 1980; 51: 607–10.
52. Iampietro PF, Chiles WD, Higgins EA, Gibbons HL. Complex performance during exposure to high temperatures. *Aerospace Med* 1969; 40: 1331–5.
53. Azer NZ, McNall PE, Leung HC. Effects of heat stress on performance. *Ergonomics* 1972; 15: 681–91.
54. Jensen RC, Haims DA. *Relationships between several prominent indices*, Cincinatti, OH: National Institute for Occupational Safety and Health (NIOSH), 1976; Publication No. 77-109).
55. Parsons KC. International heat stress standards: a review. *Ergonomics* 1995; 38: 6–22.
56. National Institute for Occupational Safety and Health (NIOSH). *The Industrial Environment, its evaluation and control*, Washington: US Government Printing Office, 1973.
57. Teichner WH. Interaction of behavioral of physiological stress reactions. *Psychol Rev* 1968; 75: 271–91.
58. Hamilton P, Hockey B, Rejman M. The place of the concept of activation in human information processing theory: an integrative approach. In: Dornic S, ed., *Attention and Performance VI*, New Jersey: Lawrence Erlbaum, 1977; 463–86.
59. Sanders AF. Toward a model of stress and human performance. *Acta Psychol* 1983; 53: 61–97.

60. Hockey R. Hamilton P. The cognitive patterning of stress states. In: Hockey GRJ, ed., *Stress and Fatigue in Human Performance*, New York: John Wiley and Sons, 1983; 331–62.
61. Duffy E. *Activation and Behavior*, New York: Wiley, 1962.
62. Hebb DO. Drives and the c.n.s. (conceptual nervous system). *Psychol Rev* 1955; 62: 243–54.
63. Lindsley DS. Emotion. In: Stevens SS, ed., *Handbook of Experimental Psychology*, New York: Wiley, 1951; 473–516.
64. Griffiths ID, Boyce PR. Performance and thermal comfort. *Ergonomics* 1971; 14: 457–68.
65. Poulton EC. Arousing stresses increase vigilance. In: Mackie RR, ed., *Vigilance: Theory, Operational Performance and Psychological Correlates*, New York: Plenum Press,1977; 423–59.
66. Wilkinson RT, Fox RH, Goldsmith R, Hampton JFG, Lewis HE. Psychological and physiological responses to raised body temperatures. *J Appl Physiol* 1964; 19: 287–91.
67. Provins KA. Environmental heat, body temperature an behavior: an hypothesis. *Aus J Psychol* 1966; 18: 118–29.
68. Hancock PA. Arousal theory, stress and performance: problems of incorporating energetic aspects of behavior onto human–machine systems function. In: Mark LS, Warm JS, Huston RL, eds, *Ergonomics and Human Factors: Recent Research*, New York: Spring-Verlag, 1987; 170–9.
69. Hancock PA, Warm JS. A dynamic model of stress and sustained attention. *Hum Factors* 1989; 31: 519–37.
70. Kahneman D. *Attention and Effort*, Englewood Cliffs, NJ: Prentice Hall, 1973.
71. Easterbrook JA. The effect of emotion on cue utilization and the organization of behavior. *Psychol Rev* 1959; 56: 183–201.
72. Chase B, Karwowski W, Benedict ME, Quesade PM, Irwin-Chase HM. Effects of thermal stress on dual task performance and attention allocation. *Ergonomics* 2001; under review.

Hancock. P.A., & Vasmatzidis, I. (2003). Effects of heat stress on cognitive performance: The current state of knowledge. International Journal of Hyperthermia, 19 (3), 355-372.