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Human occupational and performance limits under stress: the thermal environment as a prototypical example

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The authors wish to challenge the contemporary stress limits for workers exposed to adverse thermal conditions. Further, they wish to challenge the basis upon which all such occupational stress exposures are founded. It is their contention that task performance level should be the primary criterion for exposure. Change in behavioural performance efficiency is the most sensitive reflection of human response to stress. Such responses are superior as indices of incipient damaging effects compared with the traditional measurement of physiological function. Efficient and error-free performance is the principal criterion of contemporary work, especially in high-technology systems. Therefore, continuing exposure after work performance efficiency begins to fail, but before current physiological limits are reached, is inappropriate for both the safety and the productivity of the individual worker, their colleagues, and the systems within which they operate. Behavioural performance assessment should therefore supercede physiological assessment as the primary exposure criterion, although physiological measures still provide important supplementary information. A new description of such performance thresholds for heat stress is presented, together with its substantive theoretical foundation. Performance limits are of growing importance for prescriptions to all forms of occupational exposure and are critical necessities for future statements concerning comprehensive protective safety standards.

1. Introduction

The origin of contemporary occupational stress exposure standards are founded upon knowledge of the characteristics, limitations, and response to stress of the human physiological system. The study of such processes and responses has traditionally fallen within the realm of occupational health and safety. Together, the ergonomist, the safety specialist and those in occupational medicine have sought to enact standards that protect the individual worker against physiological damage. This approach directly accords with the early nature of industrial work, where the principal demand was for physical effort. In essence, the currency of heavy industrial work was physiological response. However, a growing segment of the contemporary commercial enterprise is changing its demands from physical effort to cognitive response. Despite this fundamental change, current standards are still designed to protect against physiological as compared to cognitive sources of disturbance. As a result, there is an increasing propensity for inadequate worker protection in a variety of modern occupational conditions.

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It is proposed that health and safety exposure standards should be based primarily upon behavioural response, i.e. measures of task performance itself. Such measures provide a more sensitive metric of worker condition and are directly relevant to all aspects of human work, be they either predominantly physical or predominantly cognitive in nature. Since performance productivity is the central measure of output across a wide spectrum of industrial work, the transfer of focus from physiological protection to performance assessment is liable to experience ready acceptance. In the present work, a detailed articulation of this approach is presented in respect of one form of occupational exposure, namely heat stress. The purpose is to show how this specific form of stress can represent a prototype for safety and health criteria. The foundation upon which this position is based is presented, as is the global application of this concept to widespread forms of occupational stress.

2. The case of heat stress

The National Institute for Occupational Safety and Health (NIOSH) has estimated, conservatively, that some five to ten million workers in the USA may be exposed to heat stress as a potential safety and health hazard (NIOSH 1986). In tropical and equatorial regions, the proportion of the worker population exposed to heat stress may well be higher, especially in countries that feature agrarian economies. In order to alleviate potential harm from heat stress and to protect exposed workers, a number of exposure criteria have been promulgated (Parsons 1995). Their principal aim is to provide guidelines for acceptable exposure to heat through designation of environmental conditions, exposure duration, work composition, and some rudimentary information concerning the characteristics of the individual worker (cf. NIOSH 1972). The revision of these criteria (NIOSH 1986) provides a careful and thorough evaluation of the physiological consequences of exposure to heat and the derivation of criteria designed to protect the worker engaged in heavy physical labour from heat-stress related illnesses such as heat stroke, heat syncope, heat exhaustion and other disabling conditions. In this respect, the revised criteria admirably attain their aim. Such protection guards workers engaged in traditional industrial activities, which are composed primarily of differing levels of physical activity.

However, the revised criteria neglect a large and growing segment of the industrial population whose job is to perform more cognitively demanding operations, frequently within the confines of complex operational systems. It is also the case that numerous workers have to combine different duties, where for one period they may be actively engaged in physical labour only to be controlling or monitoring equipment the next. The deletion of cognitive performance limits under heat stress in the NIOSH (1986) document was intentional (Ramsey 1995). It was suggested (see also NIOSH 1980) that an insufficiently clear picture had been developed concerning such a relationship. It is suggested that a resolution is now possible. Consequently, one purpose of the present paper is to explore heat-stress exposure limits, not founded upon the concept of physiological injury or medical illness, but predicated upon performance criteria. As the growth of cognitive, information-processing work characteristics is ubiquitous throughout contemporary industry, the necessity to consider behaviour-related exposure limits applies across the wide spectrum of occupational stress sources and is not restricted to heat stress alone. The generality of this important observation is explored in the last section of this work.

3. Derivation of criteria for exposure to heat stress

As indicated by Millar (1986), the revised heat stress criteria (NIOSH 1986) were generated as part of programmatic efforts initiated by the Occupational Safety and Health Act (US Public Law 91-596, 1970). Documents were designed to:

> provide *medical* criteria which will assure insofar as practicable that no worker will suffer diminished *health, functional capacity, or life expectancy* as a result of his (or her) work experience. (italics and parenthetical inclusion added). (Millar 1986: iii)

Following the wording of the above designation, current exposure limits for occupational stress are founded upon medical evaluations of the impact of components of the ambient surround upon physiological functioning. This natural line of development emanates from the fact that traditional concern for worker safety and health is founded in and focused through the medical profession, whose knowledge of physiological systems and the disturbances to which they are vulnerable is pre-eminent. Consequently, evolving criteria limits have been based upon the premise of avoidance of acute or chronic physiological insult to the whole organism or component sensitive organs. Such sentiments are to be applauded and the purpose of the present paper is not to disparage this approach in any way. Rather, it is to extend this protective rationale by providing a more sensitive tool for use by practitioners. That is, the assessment of behavioural efficiency.

Development of performance-based criteria is neurobiologically justified since the central nervous system displays particular sensitivity to disturbance due to stress. As a result, behavioural changes in performance capability represent an avenue through which to evaluate early and less obvious effects of occupational stress, compared with traditional peripheral physiological manifestations. From the managerial and safety standpoint such an approach has at least two useful facets. First, productivity, as generated by performance, is a prime concern of management; productivity data are under constant scrutiny. Second, with the changing nature of work, the failure of cognitive decision-making activities and operator error are becoming greater concerns as the emphasis on heavy physical labour decreases.

As medical criteria, the NIOSH (1986) recommendations are conservative and justified. However, the criteria also seek to:

> Protect against the risk of heat-induced illness and unsafe acts (and further) prevent possible harmful effects from interactions between heat and toxic, chemical, and physical agents. (Millar 1986 : iii)

However, it is commonly the case that efficient performance on a task fails before physiological limitations are reached or physiological systems are perturbed to the boundaries of their region of steady state operation. Consequently, if the workers are no longer able to adequately discharge their duties by performing the task in question in the stressful condition, why is continued exposure permitted?

This latter statement explicitly recognizes limitations to safe functioning as specified in the criteria aims cited above (see also Ramsey *et al.* 1983). To elaborate with an example, if a worker is required to monitor a display for a critical signal to initiate an important response (cf. Hancock 1984), is it advisable to continue exposure (within physiological limits) if that worker is making a significant and potentially catastrophic number of errors by missing critical signals? The submission here is that, although insufficient to cause physiological distress, such conditions cause unacceptable hazard to the worker, his or her colleagues, and the system within which they are operating. It is proposed that as performance is commonly the most sensitive systemic response to imposed environmental stress, and is the key reason for exposing the worker to many occupational sources of stress in the first place, exposure guidelines should be formulated to deal with such responses in cognitively-demanding work conditions. It is the lack of information upon these forms of performance variation that represents one major limitation of the current heat stress criteria document revision (NIOSH 1986: 32).

4. Current criteria: derivations and limitations

The first criteria developed by NIOSH (1972) did give recommended limits for a threshold of unimpaired mental performance. This curve was a direct transcription of that described by Wing (1965) from his review of then existing studies (figure 1). Having examined the extrapolations and inferences that Wing made from a survey of existing studies, Hancock (1981) re-evaluated this threshold and provided a revision of these tolerance limits based on correction of factual errors and suspect interpretations. This comparison was incorporated into a number of texts. For example, Kantowitz and Sorkin (1983: 611) observed that:

> There is currently strong disagreement about the effects of heat stress on the mental efficiency of sedentary workers. Wing (1965) performed the classic study of this problem. Wing found that mental tasks such as arithmetic and memory tasks were not affected for very short exposures (6 minutes) but that exposures of about 43 minutes to effective temperatures over 100°F did cause impairment. Wing proposed an exponential function relating exposure time, and an effective temperature (see Figure 19-6) later adopted by the National Institute for Occupational Safety and Health (NIOSH 1972) as the recommended standard for the lower limit of heat-impaired mental performance. These limits are reached before the physiological tolerance limit of the human. However, this standard has been strongly criticized as being far too conservative (Hancock 1980). A detailed reanalysis of Wing's data has led to the line in the Figure 19-6 labeled Hancock. It is close to the physiological limits, shown as the line labeled Taylor in Figure 19-6. Until this debate is resolved, cautious Human Factors Specialists will base decisions on a curve falling between the Hancock and the Wing stress tolerance functions; extremely cautious designers may prefer to use the more conservative Wing tolerance curve.

In his work on a wide variety of stress effects Hockey (1986 : 11 – 12) commented:

> Wing (1965) summarized the results of 15 studies of performance on sedentary tasks. These data have become the basis of a well-known guideline for heat limits in Industry (NIOSH 1972), illustrated in Figure 44.7. The limit of unimpaired performance at any combination of temperature and duration is well below that for physiological tolerance. A recent re-evaluation of this evidence (Hancock 1981) suggests that the upper limit is very close to that for physiological collapse. This conclusion is based on a detailed analysis of only one study (Blockley and Lyman 1951), however, and may not be representative of the effects of thermal stress on performance.

Finally, Sanders and McCormick (1987: 441) observed:

> Note that Wing (1965) had developed a curve of tolerance limits for performing mental activities similar to the curve for mental and cognitive tasks shown in Figure 15-9. However, Wing's curve was somewhat lower than Hancock's—actually a bit below the curve for tracking tasks. In discussing this difference Hancock argues that, on the basis of his synthesis, mental and cognitive abilities can be performed at a level closer to the physiological limits than is reflected by Wing's presentation. The clarification of such a difference, however, probably is still dangling.

The functions described by Hockey (1986), Kantowitz and Sorkin (1983) and Sanders and McCormick (1987) are reproduced in figure 1.

It is important to address the issues raised by these authors, since their summaries are often the first and on occasion the only source of information to individuals who are concerned with broad interdisciplinary enquiries as typified in ergonomics and human factors. The observations made by Kantowitz and Sorkin (1983) are accurate. However, the conclusions that they draw concerning standard setting are of concern. First, it must be acknowledged that the purpose of the paper by Hancock

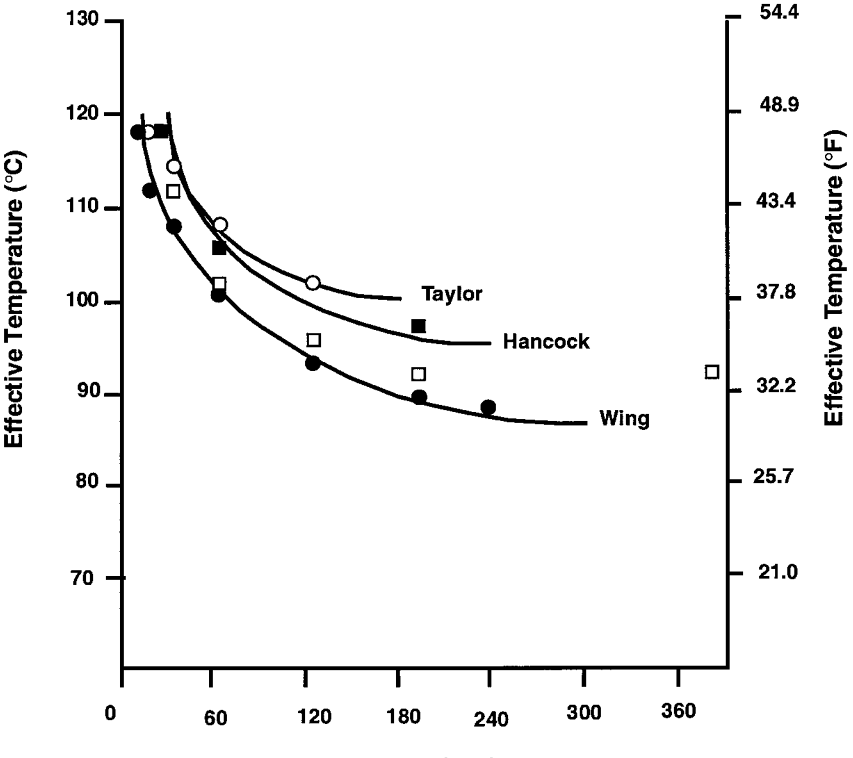

Figure 1. Revised heat stress limits of exposure for unimpaired mental performance (HANCOCK curve). The TAYLOR curve indicates physiological tolerance to heat stress (Taylor 1948). The WING curve represents the exposure limits adopted by NIOSH 1972, although the value were transcribed problematically to WBGT.

(1980) was to criticize the *factual* basis for the foundation of Wing's curve. However, the use of the respective curves as protective standards was not considered primarily in that work since the focus was on absolute tolerance itself, not on recommended limits. One obvious drawback in using Wing's curve is that NIOSH (1972) simply transcribed Wing's original curve for their use, and in so doing apparently equated Effective Temperature (ET) and Wet Bulb Globe Temperature WBGT, which is a questionable procedure. However, this does not mean that either Wing (1965) or Hancock (1980) expressly advocated their respective curves as tolerance criteria, as implied by Kantowitz and Sorkin (1983). Rather, they are the limits at which significant impairment in mental performance can be expected. Operating at these ceiling limits as a protective standard is a highly inadvisable strategy. Clearly, it is appropriate in setting tolerance criteria to adopt conservative standards. As Konz (1983) and others have pointed out, information from studies that underlie such criteria are often taken from well motivated, young college subjects, who are exposed on only one or two occasions to the debilitating effects of the stress. However, the subsequent protection is often directed toward older individuals who experience the potential for chronic as well as acute exposures and whose motivation to perform cannot be sustained at the same level for extended periods of weeks, months, or even years of operation. Compounded with these are additional concerns such as gender, fitness, task performance capability and numerous other individual differences that have to be understood before a fully comprehensive standard can be finalized (Enander and Hygge 1990). As pointed out by Hancock (1980), the standard was rightly conservative, but for essentially the wrong reason, being founded on fallacious information. This is more than mere polemics in that subsequent differentiation of tasks (Hancock 1982, 1984) indicated that some forms of performance could be expected to suffer impairment at time/intensity combinations well below those designated by Wing's curve.

Hockey's (1986) comments are problematic since they suggest that the re-evaluation by Hancock (1981) was based on only a single study, that being the report by Blockley and Lyman (1951). This is not so. The re-evaluation was actually based upon the analysis of all the studies cited by Wing (1965), and a number of reports that were published since his original paper appeared. It is true, however, that one clear factual mistake made by Wing (1965) was in his interpretation of the data given by Blockley and Lyman (1950) (not Blockley and Lyman 1951 as indicated by Hockey 1986). It is correct that this was given prominence by Hancock (1981). However, Wing's interpretation of Blockley and Lyman's (1950) data was a crucial point in that it purported to establish the exposure limit at the 1-h duration. It is not correct to assert that Hancock's (1981) whole argument was based on the results from this single study.

Sanders and McCormick (1987) pointed to the problem of task differentiation. They noted that the curves subsequently developed by Hancock (1982), and discussed in more detail below, crossed the single function given by Wing. It is important to note that in his work, Wing did not make any explicit differentiation for task performance category. In so doing he implied the equivalence between tasks that require simple mental operations (Blockley and Lyman 1950) and those involving some more complex motor responses (Pepler 1958). Hancock (1982) argued that such tasks could not be considered of homogenous cognitive demand and had to be differentiated. This tactic had also previously been advocated by other researchers (Grether 1973, Ramsey and Morrissey 1978). When such a differentiation was made, the tolerance limit curves for each category of performance tasks showed common shapes, although occurring at different absolute tolerance levels (figure 4). This important observation is discussed in more detail below.

Each of the above reviews rightly indicated the danger of extrapolating thresholds from a sparse database, and in considering the different interpretations that can be made from each supportive study. However, some of their respective equivocation does not sufficiently reflect the fact that Hancock (1981) pointed to a number of simple *factual* mistakes made by Wing (1965) in his original interpretation. Given some of these problems it is perhaps unsurprising that the limits illustrated in Wing's curve of figure 1 were not reproduced in the NIOSH revised criteria document (NIOSH 1986).

5. Single versus multiple thresholds for criteria

As it is readily apparent from the above argument, one of the limitations to Wing's curve was the way in which all forms of task performance were included in the derivation of a single threshold, regardless of their actual composition. A different perspective on performance limits was given by Ramsey and Morrissey (1978). Following the notion advanced by Grether (1973), they developed a description based on different task categories. Essentially, they distinguished two groups of tasks, one consisting principally of mental performance, and a second consisting of psychomotor performance. They rightly pointed out that for each group, a single curve could represent only the dichotomous differentiation into decrement and no decrement. Consequently, they developed isodecrement curves based upon the probability of performance failure at particular time-temperature conditions. Examples of such curves are given in figures 2 and 3. As can be seen by comparing the respective figures, there are radically different limits depending on the nature of the task. In subsequent work, Hancock (1982) sought commonalties across the limits as they applied to these different respective task categories, particularly at the upper extremes of exposure. The illustration in figure 4 shows the detailed foundation of this subsequent synthesis. As can be seen, each of the curves presents a similar shape, including the limits for physiological tolerance and these also accord with the limits presented by Meister (1976).

Different limits based upon performance differentiation were quoted by Konz (1987 : 449) in his text on work design. He stated that:

> Wing and Touchstone made a 162-reference bibliography on the effects of temperature on human performance. Wing, summarizing 15 different studies of sedentary work in heat, gave Figure 20.4 as the temperature-time trade-off for mental performance; he noted that human performance deteriorates well before physiological limits have been reached. Hancock shows the effect on different tasks in Figure 20.5. Ramsey, Dayal and Ghahramani report their own data plus other support for Wing's curve.

Konz is correct in his statements, except that because the study reported by Ramsey *et al.* was published in 1975 they had no opportunity to comment on the relationship of their findings to the multiple curves published subsequently by Hancock (1982), but now see Ramsey (1995).

The revised criteria (NIOSH 1986) give recommended alert limits and exposure limits from knowledge concerning the human physiological tolerance to heated conditions for heat acclimatized and heat unacclimatized workers, respectively. They

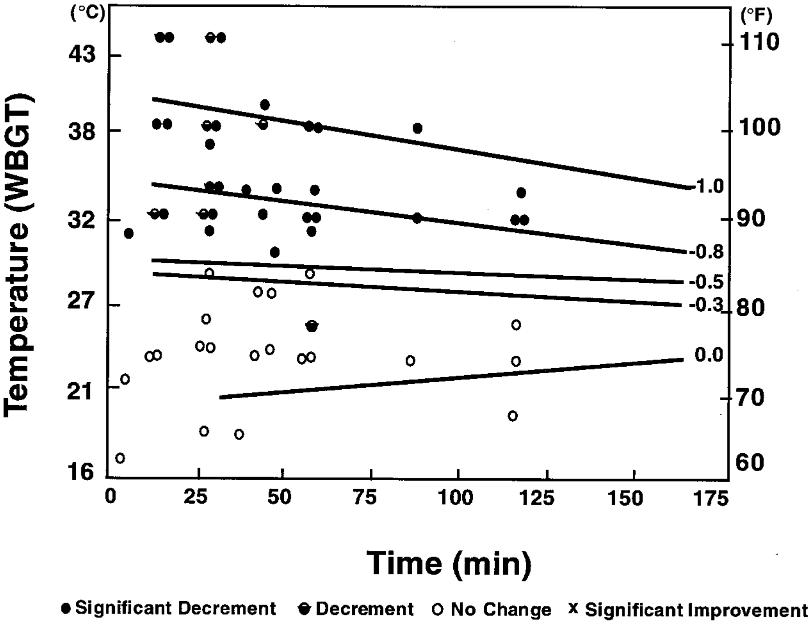

Figure 2. Isodecrement curves for mental performance tasks. The numbers represent level of performance decrement in the range from 0.0 (no change) to − 1.0 (definite significant decrement in task performance). Reprinted from Ramsey and Morrissey (1978) with kind permission from Elsevier Science.

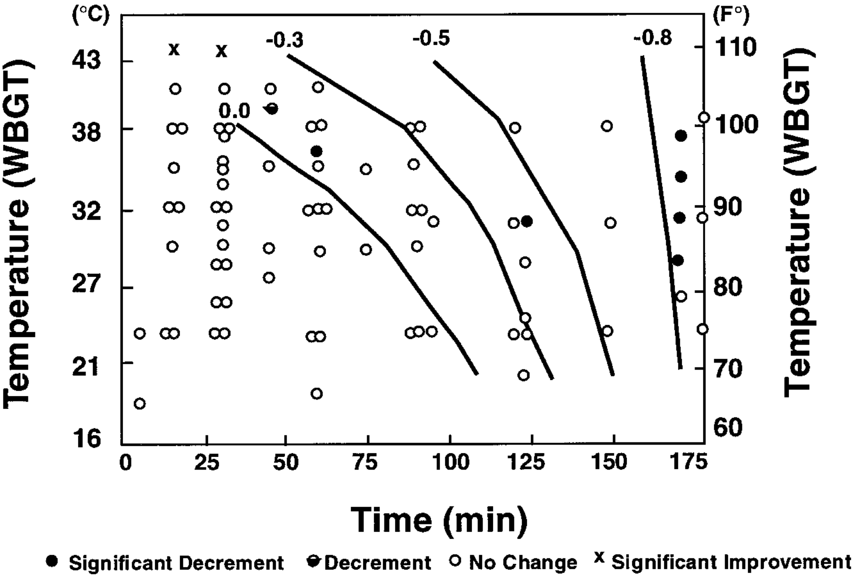

Figure 3. Isodecrement curves for tracking tasks. The numbers represent level of performance decrement in the range from 0.0 (no change) to − 1.0 (definite significant decrement in task performance). Reprinted from Ramsey and Morrissey (1978) with kind permission from Elsevier Science.

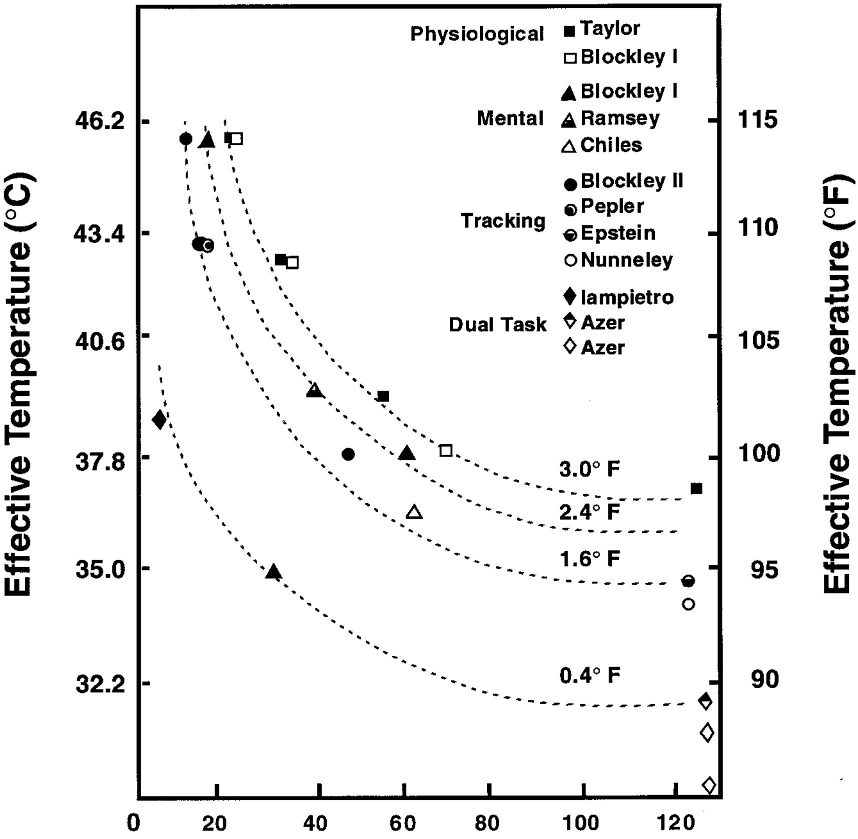

Figure 4. Heat stress limits for unimpaired performance for mental and cognitive tasks (triangular symbols), tracking tasks (circular symbols) and dual-tasks (diamond symbols). Square symbols represent physiological tolerance. Superimposed are dashed lines representative of prescribed rises in deep body temperature which accrue from time, ET intensity specifications outlined. These absolute values for the rise of body temperature are given on each curve. Names are for the first author for each study. Reprinted from Hancock (1982) with the kind permission of the Aerospace Medical Association.

represent functions of an environmental heat load, expressed in WBGT units, and worker-generated heat load. Limits are given in terms of continuous and intermittent work schedules and between illustrations for differing states of worker acclimatization. However, these limiting functions made no reference to cognitively demanding work as did its predecessor (NIOSH 1972).

In their review, Ramsey and Kwon (1992) examined results from more than 150 studies in which the impact of differing heat intensities and exposure times had been evaluated on differing forms of performance task. In keeping with their previous observations (Ramsey and Morrissey 1978), they divided these tasks into two major categories, those requiring simple mental performance, and those requiring psychomotor response. Within these categories, they established whether the examined studies showed obvious and statistically significant decrement, marginal decrement, no evidence of performance change, or performance enhancement. No comparable marginal category was given for the case of enhanced efficiency. Of critical importance for these cross-study comparisons, was the establishment of a common heat stress index that combines the characteristics of the thermal surround. As Ramsey and Kwon (1992) pointed out, much of the experimental work in this area is two to three decades old, as contemporary human-participant restrictions do not allow severe experimental heat exposures. As many early studies used the Effective Temperature (ET) scale, a participant-oriented rather than an environmentally oriented scale, some assumptions and translations were needed to establish intensity levels on a common scale. Quite properly, Ramsey and Kwon (1992) chose the WBGT scale and used the NIOSH (1972) nomogram to convert ET to CET (or Corrected Effective Temperature) units, from which WBGT values may be derived. This use of WBGT allows comparison with many current criteria documents (NIOSH 1986, ACGIH 1986, ISO 1989, Parsons 1995). Their findings are summarized in figures 5 and 6.

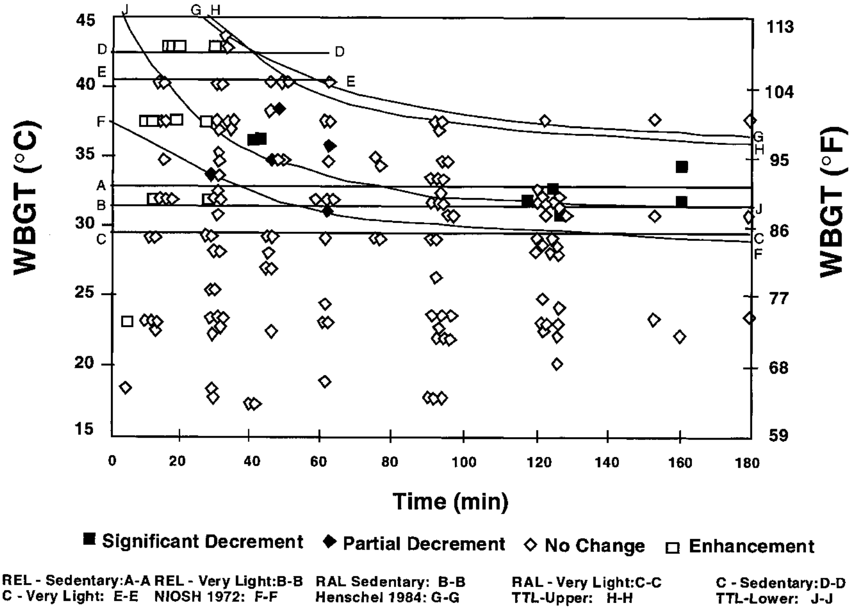

Figure 5. Mental or simple task performance in the heat and proposed temperature-time limits for human responses. REL, or Recommended Exposure Limit, applies to heat acclimatized workers, and RAL, or Recommended Alert Limit, applies to heat unacclimatized workers. Curves A-A, B-B, and C-C are exposure limits based on 1 h time-weighted averages for the case of unsteady thermal conditions. Curves D-D and E-E are the NIOSH 1986 recommended ceiling limits for sedentary and very light work, respectively. Curve G-G was derived based on personal communication between Ramsey and Kwon and Henschel (1992). Curve H-H defines the upper thermal tolerance limits (TTL-Upper) for unimpaired neuromuscular performance as specified by Hancock and Vercruyssen (1988). Curve J-J (TTL-Lower) describes the time-temperature conditions where no change in deep body temperature is expected for the sedentary worker as specified by Hancock and Vercruyssen (1988). Reprinted from Ramsey and Kwon (1992) with kind permission from Elsevier Science – NL, Sara Burgerhartstraat 25, 1055 KV Amsterdam, The Netherlands.

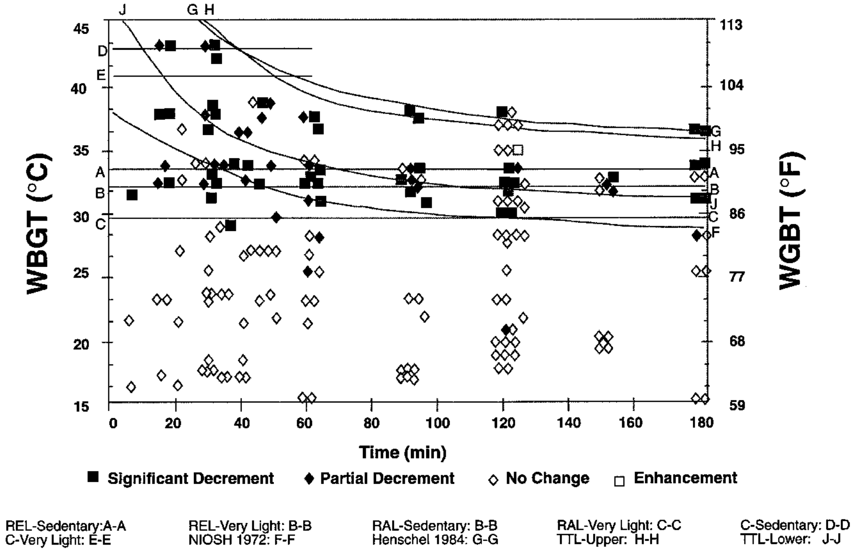

Figure 6. Perceptual motor task performance in the heat and proposed temperature-time limits for human responses. REL, or Recommended Exposure Limit, applies to heat acclimatized workers, and RAL, or Recommended Alert Limit, applies to heat unacclimatized workers. Curves A-A, B-B, and C-C are exposure limits based on 1 h time-weighted averages for the case of unsteady thermal conditions. Curves D-D and E-E are the NIOSH 1986 recommended ceiling limits for sedentary and very light work, respectively. Curve G-G was derived based on personal communication between Ramsey and Kwon and Henschel (1992). Curve H-H defines the upper thermal tolerance limits (TTL-Upper) for unimpaired neuromuscular performance as specified by Hancock and Vercruyssen (1988). Curve J-J (TTL-Lower) describes the time-temperature conditions where no change in deep body temperature is expected for the sedentary worker as specified by Hancock and Vercruyssen (1988). Reprinted from Ramsey and Kwon (1992) with kind permission from Elsevier Science – NL, Sara Burgerhartstraat 25, 1055 KV Amsterdam, The Netherlands.

Ramsey and Kwon (1992) indicate that for the category of very simple mental performance tasks, there is little evidence of decrement across the range of intensities and exposure times surveyed and that on many occasions such capabilities are enhanced during brief exposures. These results confirm the previous assertion that there is only a slight mental performance decrement before impending physiological collapse (Hancock 1981: 180). However, as with Ramsey and Kwon's (1992) additional observations, it has been noted that most tasks that require constituents of motor performance are more susceptible to heat (Hancock 1981: 180). Hancock (1982) divided psychomotor performance on the basis of single- and dual-task demands and found a number of consistencies in the data that are illustrated in figure 4.

Hancock (1982) took these respective curves and converted them from time/intensity expressions into discrete changes in core body temperature using the function described by Houghten and Yagloglou (1923). Given this translation, different levels of dynamic change to deep body temperature can be substituted for the time/intensity functions formerly illustrated as the limits for each task. These respective values were added to each boundary as shown in figure 4. A number of studies using impermeable garments that manipulated dynamic change to deep body temperature, but without variation in environmental temperature, provided data that supported these derived deep body temperature values (Allan *et al.* 1979). This convergent evidence established that it is *change* in the dynamic thermal state of the operator that influences performance, not manipulation of the physical environment *per se*. It is important to note here that elevation to a higher steady state value, as occurs when the individual can use physiological mechanisms to partially neutralize the impact of the increased ambient thermal load, does not represent dynamic or uncompensable change. So, it is the degree of change and its derivative, rate of change in deep body temperature that are crucial. Each of these factors is important when considering variations due to individual differences in capacities such as acclimation and task skill (Hancock 1986a, Enander and Hygge 1990, Enander 1997).

It is important to provide the rationale under which previous syntheses of empirical data relating heat stress to performance variation has been developed. In analogy with physical effort, Hancock (1982) suggested that the more demanding an information-processing task, the less heat strain could be sustained before performance interruption would occur. Therefore, as expressed in figure 4, a task requiring considerable cognitive effort is constrained by a more conservative limit than one requiring little cognitive effort. Hancock (1982) indicated overall performance limits in a similar manner where simple mental tasks could be performed under conditions impermissible for a complex or dual task that required the simultaneous performance of two unrelated tasks. In this way, a parallel could be drawn between the attention demands of an information-processing task and the physical demands of a materials handling task. This is *not* to suggest that each may be directly related to metabolic demand as this implies an unfounded argument for an isomorphism between physiological and cognitive effort (Hancock 1986b,c). Further, a task in which a display has to be monitored for an irregular and unexpected signal for response is particularly vulnerable to heat effects (Ramsey and Morrissey 1978, Hancock 1984, 1986b). As a result, Hancock (1982) plotted isodecrement curves for performance failure in heat that could be interpreted as limits expressed by dynamic change in deep body temperature. These were elaborated into descriptive zones of heat stress designation for the worker engaged in low metabolic demand activity (Hancock and Vercruyssen 1988), see figure 7.

6. A new descriptive framework

There is, however, a more parsimonious way to describe human performance limits under heat stress. The approach is illustrated in figures 8 and 9 and involves an alternative representation of known performance limit curves in different task categories. As shown in figure 8, the primary (horizontal) axis is exposure time. The secondary (vertical) axis is thermal intensity of the environment expressed first in terms of the traditional Effective Temperature (ET). The temporal axis extends from the brief pulse-like exposures (approximately 3 min in duration) to a time approximating a common shift, excluding meal breaks and start-up and shut-down time (approximately 7 h). The vertical axis extends from the top at which marginally tolerable conditions occur for any exposure period (i.e. 45.5°C ET) to the ceiling of Lind's (1963) prescriptive zone (29.4°C ET). The latter, prescriptive zone has more recently been termed the zone of thermal equilibration, to denote the absolute boundary of steady-state thermo-regulatory capacity (Hancock and Vercruyssen 1988).

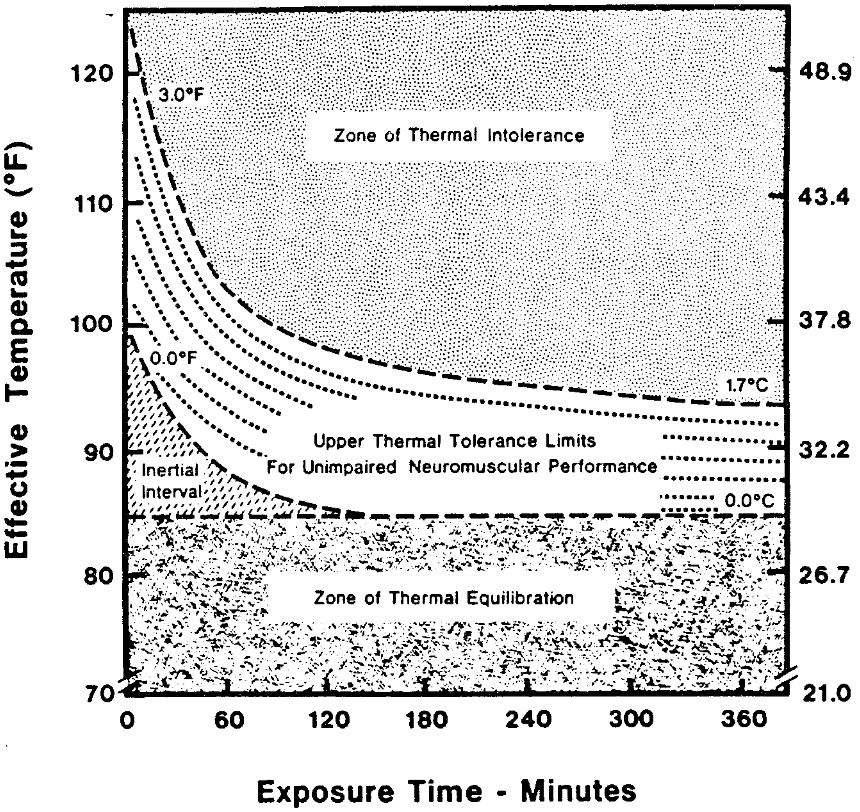

Figure 7. Differing performance zones identified by Hancock and Vercruyssen (1988). Numbers in the figure represent dynamic rise in deep body temperature. Reprinted from Hancock and Vercruysen (1988) with kind permission from Elsevier Science – NL, Sara Burgerhartstraat 25, 1055 KV Amsterdam, The Netherlands.

Within this framework, performance limit curves are plotted as parallel lines. The general form of the equation describing these performance thresholds is:

$$ET = a - b \log_e T \qquad (1)$$

where ET is Effective Temperature, T is exposure time, and a and b are empirically determined constants. In the above relationship, parameter b — the slope of the equation — is equal to -4.094 and remains constant for each task category curve. Parameter a — the intercept of the lines with the thermal intensity axis — reflects the attentional involvement required by each task category plotted. The higher the value of parameter a, the higher the respective performance limit and the lesser the respective attentional demand placed on an individual by the task.

In figure 8, performance limit curves are drawn from left to right in a decreasing attentional demand order. Initially, to the right is line E indicating the physiological tolerance ceiling. Immediately below this absolute ceiling is the performance limit for simple mental tasks represented by line D (Hancock 1981, Ramsey and Kwon 1992). This is followed by tasks requiring neuro-muscular coordination (line C). Next is line B, the threshold for dual-tasks combining each of the requirements in the two latter

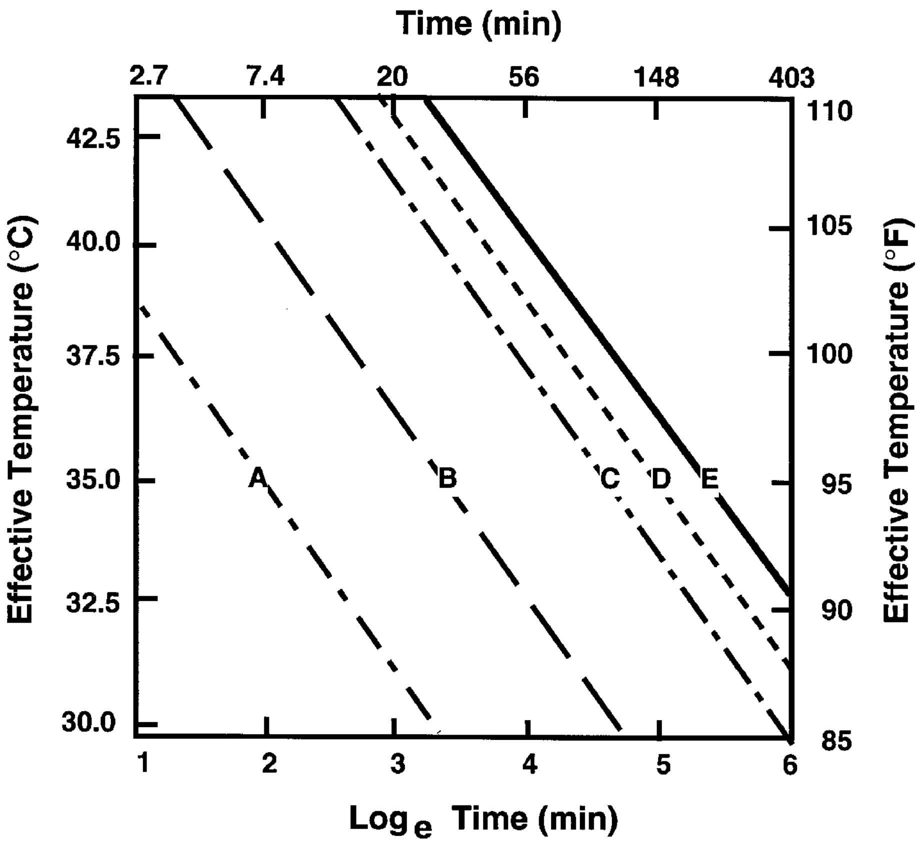

Figure 8. Human performance limits in (ET)/log$_e$(Time) Cartesian space (A: vigilance performance, B: dual-task performance, C: tracking performance, D: simple mental performance, E: physiological tolerance).

categories (Hancock 1982). A final line (line A) formed from empirical data and using the summary as presented in Hancock (1986b), describes the tolerance of sustained attention (see also Hancock 1984). Note that vigilance is particularly vulnerable to heat effects. This failure of monitoring-type behaviour is particularly pertinent to the design of operator tasks in many contemporary systems. Table 1 provides the empirical and tolerance standard adjusted intercept values for each performance curve of figure 8, when ET is expressed in terms of °C.

Although the linearity across the present plot allows for a simple mathematical description of tolerance, where task category performance threshold is defined by the intercept value, this linearity is not the major significance of the illustration. Rather, it is that each threshold describes a particular dynamic rise in deep body temperature that corresponds to the limit of efficient performance on that task. This property permits a transcription of performance limits from the Effective Temperature-time domain to the Wet Bulb Globe Temperature (WBGT)-time domain. This transcription is illustrated next and is necessary since WBGT has replaced ET as the principal metric of the environmental thermal load in most of the experimental studies conducted during the last decades (see figure 9). Consequently, WBGT was

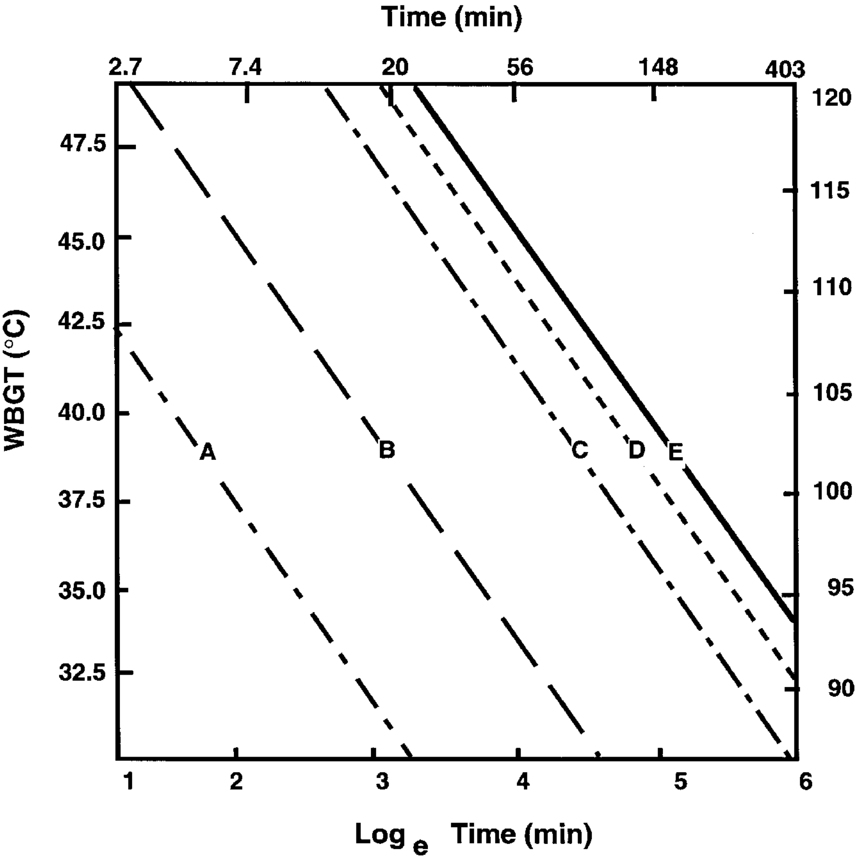

Figure 9. Human performance limits in the WBGT/log$_e$(Time), Cartesian space (A: vigilance performance, B: dual-task performance, C: tracking performance, D: simple mental performance, E: physiological tolerance).

Table 1. In respect of figure 8, since the slope is common at – 4.094, designation of each performance limit curve, in °C, can be specified by a single intercept value. There are two crucial issues to note. As the zero point on the logarithmic base goes to infinity, the intercepts shown are purely pragmatic and are used to plot the lines within the time/ intensity boundaries shown. Thus the tolerances should not be extended beyond the time/ intensity limits illustrated without further experimental validation. Second, two intercepts have been presented. The first is derived solely from the empirical data, the second contains a conservative adjustment so that the designations can be used for acceptable tolerance standards.

Curve	Task type	Empirical intercept	Tolerance adjusted intercept
A	Vigilance performance	42.82	41.0
B	Dual-task performance	48.59	47.0
C	Tracking performance	53.96	53.0
D	Simple mental performance	55.81	54.0
E	Physiological tolerance	57.06	55.0

the index incorporated in the two most recent NIOSH heat stress recommended standards (NIOSH 1972, 1986) and several other International standards (Parsons 1995). Equation (1) can be rewritten in terms of WBGT as:

$$\mathrm{WBGT} = a - b \log_e T \tag{2}$$

where the slope and intercept constants now adjusted to the new WBGT scale values, are presented in table 2.

A direct translation between ET and WBGT cannot be accomplished through the physical properties of the atmosphere without knowledge of the radiant heat value in the respective ET environment. In the paper by Ramsey and Kwon (1992) this translation was accomplished by estimation of conditions in the absence of reported data. However, a knowledge of the rate of rise of body temperature against WBGT can act as an alternate source of translation. This function is available from the work of Jensen and Heims (1976). The procedure presented here, and the estimates of Ramsey and Kwon (1992) are both superior to the unfounded equivalence between ET and WBGT assumed in the NIOSH (1972) document for drawing the curve concerning the heat stress-related performance limits as given by Wing (1965). This whole question of index selection and transcription process is worthy of further study (Parsons 1993). For the purpose of the present work, the transcription of performance limits was accomplished by employing the information in Jensen and Heims (1976). The new threshold curves are presented in figure 9, where the respective thresholds for vigilance, dual-tasks, neuro-muscular co-ordination tasks, simple mental performance and physiological tolerance are 0.055°C, 0.22°C, 0.88°C, 1.32°C and 1.65°C dynamic increases in body temperature, respectively. The slope b of the lines in figure 9 is -5.435. The empirical and tolerance adjusted intercept values for each performance line, when WBGT is measured in °C, are provided in table 2.

Within the time/intensity ranges described it is suggested that the limits illustrated in figures 8 and 9 provide the upper tolerance levels of performance in each of the task categories. These limits represent the points of statistical degradation when compared to performance in a thermo-neutral environment. The authors do not enter here into arguments that have surrounded the methodological limitations inherent in designs that use such pairwise within-subject comparisons, nor in the argument that contrasts statistical against substantial real-world performance degradation, which are obviously not necessarily coincident. Rather, the boundaries should be thought of

Table 2. In respect of figure 9, the slope is common at -5.435. Again, since the zero point on the logarithmic base goes to infinity, the intercepts shown are purely pragmatic and are used only to plot the lines within the time/intensity boundaries shown. The tolerances therefore, may not be extended beyond the time/intensity limits illustrated without further experimental validation. Again, the empirical and tolerance adjusted intercepts are specified.

Curve	Task type	Empirical intercept	Tolerance adjusted intercept
A	Vigilance performance	48.02	46.0
B	Dual-task performance	55.68	54.0
C	Tracking performance	63.11	62.5
D	Simple mental performance	65.33	64.0
E	Physiological tolerance	66.56	65.0

as critical failure points along an exponential curve relating performance to stress intensity, the latter being the product of exposure time and exposure temperature. Figure 9 indicates that, as with the observations of Ramsey and Morrissey (1978), there are a series of contours that describe states of performance degradation for which the significant decrement barrier can be regarded as one major feature. However, unlike Ramsey and Morrissey (1978), the present authors observe that the manner in which these contours are arranged represent geometric degradation rather than the linear function implied in their work. It should be noted that the tasks referred to in the present paper are performed without substantive levels of muscular or metabolic exertion. The boundary conditions, expressed as uncompensated rises in deep body temperature, may remain constant even if one source of heat stress, e.g. the environment, is augmented with another source, e.g. physical activity. However, exactly how environmental heat load and muscular heat load combine to influence cognitive performance certainly needs considerable experimental research before the above statement can be either substantiated or rejected (Vercruyssen *et al.* 1989).

7. Theoretical foundation of the limits derived

The physiological limits of tolerance to heat and associated criteria as developed in the most recent NIOSH document (1986) are founded upon a solid body of knowledge concerning human physiological response. Thus, it is incumbent to demonstrate comparable theoretical foundation for performance-based criteria. This has been elaborated previously (Hancock and Warm 1989) and as a consequence is only briefly outlined here. The theory is founded upon a direct linkage between physiological and psychological functioning. The lack of a single coherent theoretical framework that accounts for experimental findings has been the weakest point in heat stress literature as related to mental performance and for that matter in stress research in general. By far the most popular theory has been the behavioural arousal account (Duffy 1962, Provins 1966, Poulton 1977), which postulates an inverted-U relationship between the arousal level of the individual and the level of environmental stress. However, this position is unfalsifiable and can account for almost any pattern of data in a *post hoc* manner. Thus, it has often been invoked by researchers unable to find any other explanation of a seemingly contradictory data set (see Hancock 1987 for a critique of behavioural arousal theory). Without reference to a theoretical structure, there is no rationale, other than empirical separation, for dividing results into different performance categories.

In this work, tasks have been divided on the basis of attentional demands. Therefore, attentional characteristics and their variation under stress have been used as the theoretical rationale for the defined limits. This variation of attentional characteristics in the presence of environmental stress is accounted in detail by the maximal adaptability model (Hancock and Warm 1989) which is reproduced in figure 10. This model assumes that heat exerts its detrimental effects on performance by competing for and eventually draining attentional resources (Kahneman 1973).

In figure 10, the base axis is similar to Selye's (1956) conception of stress ranging from extremes of underload (hypostress) to extremes of overload (hyperstress). In the middle of this range is an area of minimal stress (the normative zone) that requires no compensation on the part of the individual. Surrounding the normative zone is the comfort zone in which cognitive adjustments to task demands are easily

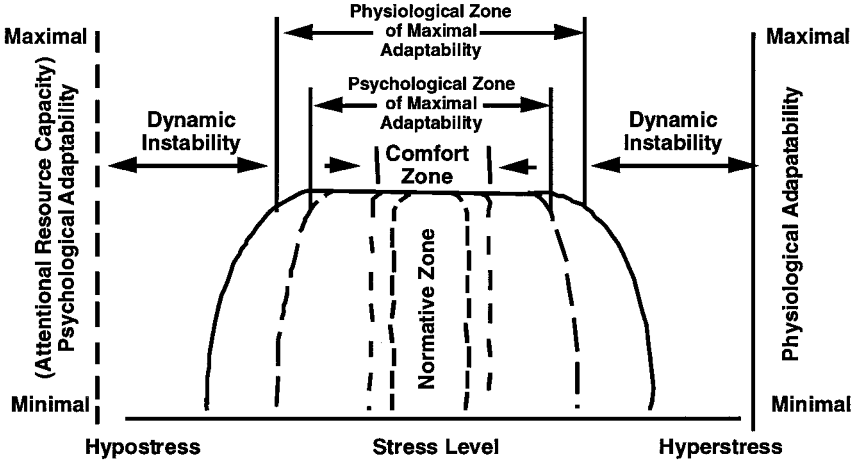

Figure 10. The maximal adaptability model. Reprinted from Hancock and Warm (1989) with kind permission.

enacted, and therefore performance remains close to its best level. As the level of stress increases away from this zone, attentional resources are progressively drained. Initially, the remaining resources are efficiently utilized by the individual, with the net result being no performance decrement, and occasionally performance enhancement (Easterbrook 1959). This behavioural pattern is a reflection of psychological adaptability and is observed inside the zone of maximal psychological adaptability. At higher stress levels, depletion of attentional resources causes progressive failure of task efficiency (see dashed line in figure 10 comprising the boundary of psychological zone of maximal adaptability; see also Hancock 1986b for a more detailed discussion). Finally, extreme levels in stressor intensity move the body outside the zone of homeostasis (physiological zone of maximal adaptability), toward the region of dynamic instability, in which the life-threatening aspects of stress exposure, such as heat stroke in heat stress, are experienced.

As illustrated in figure 10, rather than an inverted U-shaped function, the maximal adaptability model proposed an extended U-shaped function in which three modes of operation are represented. The first, the flat ceiling of the extended U, represents a mode of operation in which dynamic stability predominates. Second, at the shoulders of the extended-U, there are regions of transition. Finally, the arms of the extended-U are dynamically unstable and in the present circumstances represent incipient failure. Another characteristic of the model is its symmetric nature. Using engineering terms, this feature implies that strain increases symmetrically with progressive deviation from the central point. The function of this increase in strain is given by the solid line in figure 10, and replicates that failure occurs in the geometric form noted above. The strain function is the same for both physiological and behavioural degradation, but the parameters of the curves differ, signifying that behaviour is affected before physiological effects are observed. Recently, the maximal adaptability model has served as the basis for extensive work on the effects of stress and fatigue on a variety of real-world tasks (Matthews and Desmond 1995, Desmond and Matthews 1996, Matthews *et al.* 1996).

8. Single versus multiple resource pools

In situations where several cognitive tasks have to be performed at the same time, the maximal adaptability model assumes initially that the stress of response to hot conditions drains attentional resources from a single, undifferentiated attentional resource pool. Expanding this notion into conditions requiring the allocation of spatial attention, where an individual is required to perform concurrent tasks in both the central visual field and the peripheral visual field, it can be concluded that the dominant form of failure sees attentional resources drained from peripheral processing before degradation in central processing. This 'funneling of attention' has been reported by Bursill (1958) and by Poulton *et al.* (1974), among others.

Vasmatzidis *et al.* (1995) evaluated the assumption of resource depletion from a single, undifferentiated resource pool of attention. They used the stages, modes, and functions model developed by Shingledecker (1984) to evaluate differentiated resource depletion under heat stress. Their results indicated that perceptual input as required by a visual monitoring task, and response output, as required by an unstable tracking task, were the most sensitive to heat effects when paired with a central processing, mathematical task and a mental processing, memory search task respectively (for a detailed discussion see Vasmatzidis 1995).

With respect to more complex performance, where three or more tasks are time-shared, Iampietro *et al.* (1969) provided indictions that psychomotor performance fails first when concurrently performed with a working memory and sustained attention task. Vasmatzidis (1995) found similar patterns of evidence using a multi-task scenario requiring mathematical processing, memory search, visual monitoring, and auditory discrimination. Here, the auditory discrimination task proved most vulnerable to heat stress effects. Unfortunately, there are very few existing studies that report on these complex multi-task performance conditions, although they are very likely to be those encountered in the actual workplace. Obviously, more information is required in this vein in order to make firm statements about such important performance limitations. A framework for such a systematic investigation has been proposed by Vasmatzidis and Schlegel (1994). Until such a programme of work is conducted, it would be unwise to make any simplistic assertions about these multiple task conditions and the way in which performance is liable to fail under heat stress.

9. Implications for all stress criteria

The present work has implications for developing criteria for all types of occupational stress exposure. Previous derivations of exposure criteria have been founded upon medical science and are intended to ensure the healthy functioning of the human physiological system. Ergonomists have been comfortable with this approach, especially considering the role of physiology in the foundation of ergonomics itself. However, the change in the nature of contemporary work has broad and far-reaching effects. One crucial effect is the transformation of the currency of a growing proportion of work from physical energy to information. However, many situations remain in which physical effort is not important; but it is recognized that information has emerged as the currency of the work in numerous cognitively taxing environments and such performance and associated mental error are now vital concerns for ergonomists and system specialists.

In the past, injuries were physical and criteria were derived to protect against such physical sources of occupational threat. Today, at least as much emphasis is placed on understanding cognitive over-exertion or more appropriately, mental workload (Hancock and Warm 1989, see also Miller 1960). In the present work it has been argued that heat stress exposure criteria which are designed to protect against physical harm, do not always suffice for cognitive work. It is postulated that the active nervous central system and its performance output is predominantly the most vulnerable element of the worker. Thus, it is performance that needs to be protected and consequently should comprise the major focus of future heat stress exposure criteria.

It is proposed that the present description is not constrained to heat stress alone. Rather, it is suggested that many additional sources of occupational stress may be captured using the same form of description and the same underlying model, although the specific parameters will change depending on the nature of stress involved. The present framework can also serve as a basis for understanding the multiple interaction of stresses that has always been a highly problematic issue (Hancock and Pierce 1985, see also NIOSH 1986). The great advantage of the present construct is the employment of attention as the basis for formulation. Consequently, the different cognitive demands of the tasks, which *themselves* are frequently the main source of occupational stress, can be easily incorporated into this framework. No previous proposal has allowed the inclusion of such a critical contemporary work factor into exposure limitations.

While the authors have provided a framework for understanding the commonalties of performance degradation under different forms of occupational stress, much remains to be accomplished. In common with other commentators, the authors are aware that data upon which current standards are erected have several intrinsic gaps. They do not yet contain sufficient information on how individual factors such as age and gender affect capability. Neither do they know how the effects of increasing task skill over a period of time offsets the long-term influence of chronic exposures. Certainly, much experimental research is needed to elaborate the present framework into a complete picture. Also, the databases on different respective sources of stress are at radically different stages of development. One further caution is also important. The limits expressed in figure 9 should not be used directly as an exposure standard. At the very least some conservative adjustment, via a reduction in the relative intercept values, needs to be introduced in order to permit acceptable performance levels. For this reason such adjustments have been introduced to the intercepts presented in tables 1 and 2. These conservative intercept values can be used as a basis for an exposure standard for these forms of performance in the specific thermal conditions. Consequently the present approach is a viable avenue through which to pursue standard setting and the framework given is sufficiently comprehensive to permit the development of standards for different forms of occupational stress within a common model.

10. Summary and conclusions

The nineteenth and the early twentieth centuries have been characterized as the industrial age, whereas the late twentieth century and the coming millennium are better described as the information age. The associated transformation of human work has had its effects on all segments of society but on none so much as on those who seek to understand, describe and use the laws of work to our collective benefit. In its foundation and growth, ergonomics has sought to protect the worker from sources of threat so that work can be carried on in a safe and productive manner. However, many of the stress exposure criteria that seek to attain this goal now need to be changed in the light of the changing nature of work. The authors have argued that the basis of worker protection must shift from physiological concerns to information-processing evaluation and have elaborated on the specific example of exposure to heat stress. Thus, cognitive science with its study of behavioural performance response must play a much greater, if not primary, role in the development of the exposure criteria than it has done previously. Fortunately, physiological and psychological response to stress can be promoted within a common framework that emphasizes their similarities, not their disparities. Thus, exposure criteria can be developed that integrate an understanding of behavioural response to work demands with physiological adjustment to environmental conditions. Such a unified framework promises to provide the foundation for understanding protection from all sources of threat to workers' health, safety and performance.

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References

Allan, J. R., Gibson, T. M. and Green, R. G. 1979, Effects of induced cyclic changes of deep body temperature on task performance, *Aviation, Space and Environmental Medicine*, **50,** 585 – 589.

American Conference of Governmental Industrial Hygienists (ACGIH) 1986, *Threshold Limit Values and Biological Exposure Indices for 1986 – 87* (Cincinnati, OH: ACGIH).

Azer, N. Z., McNall, P. E. and Leung, H. C. 1972, Effects of heat stress on performance, *Ergonomics*, **15,** 681 – 691.

Blockley, W. V. and Lyman, J. H. 1950, 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, Wright-Patterson Air Force Base, OH.

Blockley, W. V. and Lyman, J. H. 1951, 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, Wright-Patterson Air Force Base, OH.

Bursill, A. E. 1958, The restriction of peripheral vision during exposure to hot and humid conditions, *Quarterly Journal of Experimental Psychology*, **10,** 113 – 129.

Chiles, W. D. 1958, Effects of elevated temperatures on performance of a complex mental task, *Ergonomics*, **2,** 89 – 96.

Desmond, P. A. and Matthews, G. 1996, Task-induced fatigue effects on simulated driving performance, in A. G. Gale (ed.), *Vision in Vehicles VI* (Amsterdam: North-Holland).

Duffy, E. 1962, *Activation and Behavior* (New York: Wiley).

Easterbrook, J. A. 1959, The effect of emotion on cue utilization and the organization of behaviour, *Psychological Review*, **66,** 183 – 201.

Enander, A. 1997, Effects of extreme temperatures on mental and cognitive performance, in *Proceedings of the 13th Triennial Congress of the International Erogonomics Association*, Finnish Institute of Occupational Health, Helsinki, Finland, 518 – 520.

Enander, A. E. and Hygge, S. 1990, Thermal stress and human performance, *Scandinavian Journal of Work Environment and Health*, **16,** 44 – 50.

Epstein, Y., Keren, G., Moisseiev, J., Gasko, O. and Yachin, S. 1980, Psychomotor deterioration during exposure to heat, *Aviation, Space and Environmental Medicine*, **51,** 607 – 610.

Grether, W. F. 1973, Human performance at elevated environmental temperatures, *Aerospace Medicine*, **44,** 747 – 755.

Hancock, P. A. 1980, Mental performance impairment in heat stress, *Proceedings of the 29th Meeting of the Human Factors Society*, Human Factors Society, Santa Monica, CA, **24,** 363 – 366.

HANCOCK, P. A. 1981, Heat stress impairment of mental performance: a revision of tolerance limits, *Aviation, Space and Environmental Medicine*, **52,** 177 – 180.

HANCOCK, P. A. 1982, Task categorization and the limits of human performance in extreme heat, *Aviation, Space and Enviromental Medicine*, **53,** 778 – 784.

HANCOCK, P. A. 1984, Effects of environmental temperature on display monitoring performance: an overview with practical implications, *American Industrial Hygiene Association Journal*, **45,** 122 – 126.

HANCOCK, P. A. 1986a, The effect of skill on performance under an environmental stressor, *Aviation, Space and Environmental Medicine*, **57,** 59 – 64.

HANCOCK, P. A. 1986b, Sustained attention under thermal stress, *Psychological Bulletin*, **99,** 263 – 281.

HANCOCK, P. A. 1986c, Stress and adaptability, in G. R. J. Hockey, A. W. K. Gaillard and M. G. H. Coles (eds), *Energetics and Human Information Processing* (Dordrecht: Martinus Nijhoff), 243 – 251.

HANCOCK, P. A. 1987, Arousal theory, stress and performance: problems of incorporating energetic aspects of behaviour onto human-machine systems function, in L. S. Mark, J. S. Warm and R. L. Huston (eds), *Ergonomics and Human Factors: Recent Research*, (New York: Springer-Verlag), 170 – 179.

HANCOCK, P. A. and PIERCE, J. O. 1985, Combined effects of heat and noise on human performance: a review, *American Industrial Hygiene Association Journal*, **46,** 555 – 566.

HANCOCK, P. A. and VERCRUYSSEN, M. 1988, Limits of behavioural efficiency for workers in heat stress, *International Journal of Industrial Ergonomics*, **3,** 149 – 158.

HANCOCK, P. A. and WARM, J. S. 1989, A dynamic model of stress and sustained attention, *Human Factors*, **31,** 519 – 537.

HOCKEY, G. R. J. 1986, Changes in operator efficiency as a function of environmental stress, fatigue and circadian rhythms, in K. R. Boff, L. Kauffman and J. P. Thomas (eds), *Handbook of Perception and Human Performance* (New York: Wiley), chapter 44.

HOUGHTEN, F. C. and YAGLOGLOU, C. P. 1923, Determining lines of equal comfort, *Transactions of the American Society of Heating and Ventilating Engineers*, **29,** 163 – 176.

IAMPIETRO, P. F., CHILES, W. D., HIGGINS. E. A. and GIBBONS, H. L. 1969, Complex performance during exposure to high temperatures, *Aerospace Medicine*, **40,** 1331 – 1335.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (ISO) 1989, Hot environments—Estimation of the heat stress on working man based on WBGT index, ISO 7243 (Geneva: ISO).

JENSEN, R. C. and HEIMS, D. A. 1976, *Relationships Between Several Prominent Indices*, NIOSH publication no. 77 – 109 (Cincinnati, OH: NIOSH).

KAHNEMAN, D. 1973, *Attention and Effort* (Englewood Cliffs, NJ: Prentice-Hall).

KANTOWITZ, B. H. and SORKIN, R. D. 1983, *Human Factors: Understanding People-System Relationships* (New York: Wiley).

KONZ, S. 1983, *Work Design: Industrial Ergonomics*, 2nd edn (New York: Wiley).

LIND, A. R. 1963, Physiological effects of continuous or intermittent work in the heat, *Journal of Applied Physiology*, **18,** 57 – 60.

MATTHEWS, G. and DESMOND, P. A. 1995, Stress as a factor in the design of in-car driving enhancement systems, *Le Travail Humain*, **58,** 109 – 129.

MATTHEWS, G., SPARKES, T. J. and BYGRAVE, H. M. 1996, Attentional overload, stress, and simulated driving performance, *Human Performance*, in press.

MEISTER, A. 1976, Heat exposure, performance reliability and efficiency, *Zeitschrift fur Psychologie Mit Zeitschrift fur Angewandte Psychologie*, **184,** 63 – 72.

MILLAR, J. D. 1986, Foreword in: *Criteria for a recommended Standard: Occupational Exposure to Hot Environments Revised Criteria*, NIOSH publication no. 86 – 113 (Cincinnati, OH: NIOSH).

MILLER, J. G. 1960, Information input overload and psychopathology, *American Journal of Psychiatry*, **116,** 695 – 704.

NATIONAL INSTITUTE FOR OCCUPATIONAL SAFETY AND HEALTH (NIOSH) 1972, *Criteria for a Recommended Standard—Occupational Exposure to Hot Environments*, NIOSH publication no. 72-10269. (Cincinnati, OH: NIOSH).

National Institute for Occupational Safety and Health (NIOSH) 1980, NIOSH publication no. 81-08 *Proceedings of a Workshop on Recommended Heat Stress Standards*, F. N. Dukes-Dobos and A. Henschel (eds). (Cincinnati, OH: NIOSH).

National Institute for Occupational Safety and Health (NIOSH) 1986, *Criteria for a Recommended Standard: Occupational Exposure to Hot Environments Revised Criteria*, NIOSH publication no. 86 – 113 (Cincinnati, OH: NIOSH).

Nunneley, S. A., Dowd, P. J., Myhre, L. G., Stribley, R. F. and McNee, R. C. 1979, Tracking-task performance during heat stress simulating cockpit conditions in high-performance aircraft, *Ergonomics*, **22,** 549 – 555.

Parsons, K. C. 1993, *Human Thermal Environments* (London: Taylor & Francis).

Parsons, K. C. 1995, International heat stress standards: a review, *Ergonomics*, **38,** 6 – 22.

Pepler, R. D. 1958, Extreme warmth and sensorimotor coordination, *Journal of Comparative and Physiological Psychology*, **14,** 383 – 486.

Poulton, E. C. 1977, Arousing stresses increase vigilance, in R. R. Mackie (ed), *Vigilance: Theory, Operational Performance and Physiological Correlates (New York: Plenum Press*), 423 – 459.

Poulton, E. C., Edwards, R. S. and Colquhoun, W. P. 1974, The interaction of a loss of a night's sleep with mild heat: task variables *Ergonomics*, **17,** 59 – 73.

Provins, K. A. 1966, Environmental heat, body temperature and behaviour: an hypothesis, *Australian Journal of Psychology*, **18,** 118 – 129.

Ramsey, J. D. 1995, Task performance in heat: a review, *Ergonomics*, **38,** 154 – 165.

Ramsey, J. D. and Kwon, Y. G. 1992, Recommended alert limits for perceptual motor loss in hot environments, *International Journal of Industrial Ergonomics*, **9,** 245 – 257.

Ramsey, J. D. and Morrissey, S. J. 1978, Isodecrement curves for task performance in hot environments, *Applied Ergonomics*, **9,** 66 – 72.

Ramsey, J. D., Burford, C. L., Beshir, M. Y. and Jensen, R. C. 1983, Effects of workplace thermal conditions on safe work behaviour, *Journal of Safety Research*, **14,** 105 – 114.

Ramsey, J. D., Dayal, D. and Ghahramani, B. 1975, Heat stress limits for the sedentary worker, *American Industrial Hygiene Association Journal*, **36,** 259 – 265.

Sanders, M. S. and McCormick, E. J. 1987, *Human Factors in Engineering and Design* 6th edn (New York: McGraw-Hill).

Selye, H. A. 1956, *The Stress of Life* (New York: McGraw-Hill).

Shingledecker, C. A. 1984, A task battery for applied performance assessment, Technical report AFAMRL-TR-84-071, Air Force Medical Research Laboratory, Wright Patterson Air Force Base, OH.

Taylor, C. L. 1948, Interim report to the committee on Aviation Medicine, National Research Council, Washington, DC.

Vasmatzidis, I. 1995, Effects of heat stress on dual-task and complex mental performance, unpublished doctoral dissertation, University of Oklahoma.

Vasmatzidis, I. and Schlegel, R. E. 1994, A methodology for investigating heat stress selectivity effects on mental performance, *Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting* (Santa Monica, CA: Human Factors and Ergonomics Society), 510 – 514.

Vasmatzidis, I., Schlegel, R. E., Purswell, J. L. and Hancock, P. A. 1995, Cognitive resource depletion under heat stress, *Proceedings of the Konz/Purswell Occupational Ergonomics Symposium*, Norman, OK, 91 – 98.

Vercruyssen, M., Hancock, P. A. and Mihaly, T. 1989, Time estimation performance before, during, and following physical activity, *Journal of Human Ergology*, **18,** 169 – 179.

Wing, J. F. 1965, Upper thermal tolerance limits for unimpaired mental performance, *Aerospace Medicine*, **36,** 960 – 964.

Hancock, P.A., & Vastimidis, I. (1998). Human occupational and performance limits under stress: The thermal environment as a prototypical example. Ergonomics, 41 (8), 1169-1191.