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Literature Review: Cognitive Effects of Thermal Strain

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Abstract

This report reviews the literature on cognitive effects of thermal strain. Early research focused on the relationship between ambient temperature and various cognitive tasks including sensory, vigilance, reaction time, etc. More recent work has focused on the prescription of tolerance limits as well as attempts to generate a conceptual model to explain and predict the effects of heat on cognitive performance.

In general, it was found that investigations relating thermal strain indicators, such as core temperature, to cognitive performance are sparse; the majority control and manipulate ambient temperature. Likewise, the isolation of other factors that may interact with heat to affect cognitive performance is infrequent. This report presents findings on the interaction effects of acclimatization, hydration level and operator skill, on human cognitive performance.

Recent attempts have been made to conceptually model the effects of stress (i.e. heat) on human performance. In this review, three qualitative models are discussed and compared. The literature review failed to uncover any quantitative models.

Finally, conclusions are made with respect to the need for research that is applicable to real-world, high-risk tasks in which cognitive performance is crucial such as fire fighting or military operations.

Résumé

Le présent rapport passe en revue la littérature portant sur les effets cognitifs de la contrainte thermique. Les premières recherches étaient axées sur le lien entre la température ambiante et diverses tâches cognitives, y compris les tâches sensorielles, la vigilance, le temps de réaction, etc. Les travaux plus récents ont été concentrés sur la prescription de limites de tolérance ainsi que sur les tentatives visant à produire un modèle conceptuel pour expliquer et prévoir les effets de la chaleur sur le rendement cognitif.

De façon générale, on a constaté que les recherches établissant un lien entre les indicateurs de la contrainte thermique, comme la température centrale, et le rendement cognitif sont rares; la majorité d'entre elles consistent à contrôler et à manipuler la température ambiante. De la même façon, il est rare que les chercheurs aient tenté d'isoler les autres facteurs pouvant interagir avec la chaleur pour influer sur le rendement cognitif. Ce rapport présente les résultats d'études sur les effets sur le rendement cognitif de l'interaction de l'acclimatation, du niveau d'hydratation et des compétences de l'opérateur.

Récemment, on a tenté d'élaborer un modèle conceptuel des effets du stress (c.-à-d. de la chaleur) sur le rendement humain. Dans la présente analyse documentaire, on décrit et on compare trois modèles qualitatifs. L'analyse documentaire n'a pas permis de mettre au jour des modèles quantitatifs.

Enfin, on tire des conclusions quant à la nécessité d'effectuer des études applicables à des tâches à risque élevé réelles, pour lesquelles le rendement cognitif est crucial, telles les opérations de lutte contre l'incendie ou les opérations militaires.

Executive Summary

The objective of this literature review is to identify the quantitative relationships among thermal strain factors that significantly affect mental performance to produce a body of knowledge that can be used to develop computational models.

This report reviews research literature pertaining to cognitive effects of thermal strain. Research on the effects of heat on human mental or cognitive performance has been ongoing for over half a century. Earlier research arose from the aerospace community and focused on the effects of different combinations of ambient temperature, relative humidity and duration time, on the performance of several categories of mental tasks including reaction time, sensory, vigilance, psychomotor, tracking, dual tasks, memory and cognition.

More recent work in the area of cognitive performance in thermal environments focuses on the prescription of tolerance limits as well as the attempt to generate a conceptual model that can be used to explain as well as predict the effects of heat on cognitive performance.

This review outlines various exposure limits that have been adopted. Most of the time-temperature exposure limits are expressed in various heat stress indices related to ambient temperature. More recent work has generated time-temperature thresholds in terms of rate of change in body temperature, which is more valuable in creating computational models of cognitive effects of thermal strain.

It was determined that, out of several possible physiological indicators of heat strain, core temperature is the primary variable that has been controlled or independently manipulated in work investigating the effects of thermal strain on cognitive performance. However, investigations relating core temperature to cognitive performance are sparse.

Several researchers have acknowledged that it is virtually impossible to disentangle the effects of heat from other variables that may affect cognitive performance. Numerous other factors such as acclimatization, dehydration, clothing, fatigue, complexity of tasks and operator skill have been noted as possible intervening variables in the study of cognitive effects of thermal environments. In this report, the contributing effects of acclimatization, hydration level and operator skill on cognitive performance in thermal environments are discussed.

This report also examines models that attempt to explain and predict the effects of stress (i.e. heat) on human performance. The models examined are qualitative and are based on stress and arousal, stress in relation to human information processing and psychological and physiological adaptability in response to stress. The literature review failed to reveal any quantitative models.

In conclusion, research in the area of thermal strain and cognitive performance is slowly becoming more rigorous in terms of the types of cognitive tasks used and the inclusion of thermal strain (i.e. core temperature) as an independent variable rather than ambient temperature. As well, the recent emphasis on conceptual models will help to explain as well as predict the effects of thermal strain on cognitive performance. Nevertheless, there remains a need for research that is applicable to real-world tasks in which cognitive performance is crucial, such as fire fighting or military operations.

Sommaire

La présente analyse documentaire a pour objet de déterminer les liens quantitatifs entre les facteurs de stress thermique qui nuisent au rendement intellectuel afin de produire un corpus de connaissances qui pourra servir à l'élaboration de modèles computationnels.

Ce rapport passe en revue les comptes rendus de recherche portant sur les effets cognitifs de la contrainte thermique. Depuis plus d'un demi-siècle, on étudie les effets de la chaleur sur le rendement mental et cognitif. Les premières recherches ont été entreprises à l'instigation de la communauté aérospatiale et étaient axées sur les effets de différentes combinaisons de température ambiante, d'humidité relative et de durée sur le rendement au regard de plusieurs catégories de tâches mentales, y compris le temps de réaction, les tâches sensorielles, la vigilance, les tâches psychomotrices, le suivi visuel, les doubles tâches, la mémoire et la cognition.

Les travaux plus récents dans le domaine du rendement cognitif dans différents environnements thermiques ont porté sur la prescription de limites de tolérance ainsi que sur les tentatives visant à élaborer un modèle conceptuel pouvant servir à expliquer et à prévoir les effets de la chaleur sur le rendement cognitif.

Cette analyse donne un aperçu des diverses limites d'exposition qui ont été adoptées. La plupart des limites d'exposition temps-température sont exprimées en tant qu'indices de stress thermique liés à la température ambiante. Des études plus récentes ont permis d'établir des seuils limites temps-température en fonction du taux de variation de la température corporelle, qui constitue un paramètre plus intéressant pour la création de modèles computationnels des effets cognitifs de la contrainte thermique.

Il a été déterminé que, parmi plusieurs indicateurs physiologiques possibles de la contrainte thermique, la température centrale est la principale variable qui a été contrôlée ou manipulée de façon indépendante dans le cadre des recherches sur les effets de la contrainte thermique sur le rendement cognitif. Toutefois, les recherches établissant un lien entre la température centrale et le rendement cognitif sont rares.

Plusieurs chercheurs reconnaissent qu'il est presque impossible de dissocier les effets de la chaleur des autres variables pouvant affecter le rendement cognitif. De nombreux autres facteurs, tels l'acclimatation, la déshydratation, les vêtements, la fatigue, la complexité des tâches et les compétences de l'opérateur, pourraient être considérés comme des variables intermédiaires dans l'étude des effets cognitifs des environnements thermiques. Dans le présent rapport, on analyse les effets de l'acclimatation, du niveau d'hydratation et des compétences de l'opérateur sur le rendement cognitif dans différents environnements thermiques.

Il est également question dans ce rapport des modèles qui tentent d'expliquer et de prévoir les effets du stress (c.-à-d. de la chaleur) sur le rendement humain. Il s'agit de modèles qualitatifs fondés sur le stress et l'éveil, le rapport entre le stress et le traitement humain de l'information ainsi que l'adaptabilité psychologique et physiologique au stress. L'analyse documentaire n'a pas permis de mettre au jour des modèles quantitatifs.

Pour conclure, la recherche dans le domaine de la contrainte thermique et du rendement cognitif devient lentement plus rigoureuse en raison des types de tâches cognitives utilisées et de l'inclusion de la contrainte thermique (c.-à-d. de la température centrale), à la place de la température ambiante, en tant que variable indépendante. En outre, l'importance accordée depuis peu aux

modèles conceptuels aidera à expliquer et à prévoir les effets de la contrainte thermique sur le rendement cognitif. Néanmoins, il faut effectuer des recherches applicables à des tâches réelles, dans le cadre desquelles le rendement cognitif est crucial, telles les opérations de lutte contre l'incendie ou les opérations militaires.

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1. Introduction

This report represents the findings of a literature review of the cognitive effects of thermal strain. According to the Statement Of Work (SOW), the objective of this literature review is to "identify the quantitative relationships among thermal strain factors that significantly affect mental performance to produce a body of knowledge that can be used to develop computational models."

Defence Research and Development Canada (DRDC) Toronto is interested in developing computational models of thermal strain and mental performance. To support this initiative, DRDC Toronto requires a body of knowledge on the effects of heat strain on mental performance. This body of knowledge must provide an understanding of:

- The physiological indicators of heat strain that significantly affect cognitive performance;
- Published quantitative models relating heat strain to mental performance, or, if none are available, qualitative relationships among variables;
- Sources of data that can be used to create or validate quantitative models of heat strain and mental performance; and,
- Other, external factors that have an impact or interaction with heat strain and mental performance relationships.

In pursuit of this information, DRDC Toronto has sponsored a contract to conduct a literature review into the cognitive effects of thermal strain.

The current project has been contracted to Human*systems* Incorporated® as callup **#7879-05**. The Scientific Authority (SA) for this work is Brad Cain.

1.1. OBJECTIVE

The stated objective of this contract is to identify the quantitative relationships among thermal strain factors that significantly affect mental performance to produce a body of knowledge that can be used to develop computational models.

In order to achieve this, the following objectives were met:

1. Identify literature search keywords and databases (assume limited keywords and two databases);
2. Conduct search;
3. Select and obtain literature (assume no more than 10 most relevant);
4. Review the literature and identify the following:
    - operator state variables that have a significant effect on performance
    - cognitive performance effects due to operator state variability
    - any interaction effects, especially with reference to non-thermal factors
    - quantitative relationships between operator state variables and mental performance
    - sources of data for developing quantitative models of relationships;

5. Write a report summarizing findings;
6. Provide SA with all reference articles and sources of data.

This report outlines the approach to searching for literature and the literature review itself. Some conclusions are made following the review of the literature.

2. Methods

2.1. Databases and Keywords

Respecting the constraints of the contract, the literature search was limited to two databases. Given the topic of the literature review, it was determined that Ergonomics Abstracts and PsychInfo databases would be the most appropriate.

The following keywords (see Table 1) were used in combination to search the databases. The words were used in combination (one word associated with "heat" and one word associated with "cognitive effects" and/or "psychomotor effects"). If an unmanageable number of hits results from a search with just two words, additional keywords would be used to focus the results.

Table 1: Keywords used in the literature search

Heat	Cognitive effects	Psychomotor effects
Heat	Cognition	Reaction time
Hot	Vigilance	Coordination
Temperature	Reasoning	Motor skills
Thermal	Memory	
Core temperature	Decision making	
Skin temperature	Fatigue	
Hydration/Dehydration	Error	
Electrolyte imbalance	Mental performance	
Hyperthermia	Psychological performance	

Additionally, some papers were obtained that were referenced in those papers found by means of the initial keyword search.

2.2 Review of Literature

The criteria above led to the selection of 33 references. All of these references were obtained and reviewed, although this literature review focuses on 12 of the most relevant references.

3. Results

In total 33 references were selected and reviewed. From those 33, the 12 most relevant were selected and included in this review. The references were reviewed in order to identify the following:

- Physiological indicators of heat strain that significantly affect cognitive performance;
- Other factors that may interact to affect cognitive performance;
- Quantitative models relating heat strain to cognitive performance;
- Sources of data for developing or validating quantitative models of heat strain and mental performance, and,
- Other references to articles found serendipitously that may be suitable for creating quantitative models for physical performance as functions of heat strain.

3.1. Background

Research on the effects of heat on human mental or cognitive performance has been ongoing for over half a century. Much of the early experimental work dates back to the 1950s, following World War II. From the late 1950's until the early 1980's, research focused on the effects of different combinations of ambient temperature, relative humidity and duration time, on the performance of several categories of mental tasks including reaction time, sensory, vigilance, psychomotor, tracking, dual tasks, memory and cognition. Much of this research resulted from the aerospace community. Grether (1973), Ramsey and Morrisey (1978), Kobrick and Fine (1983), and Kobrick and Johnson (1992) provide comprehensive reviews of these investigations.

More recent work in the area of cognitive performance in thermal environments focuses on the prescription of tolerance limits as well as the attempt to generate a conceptual model that can be used to explain as well as predict the effects of heat on cognitive performance.

3.2. Tolerance limits for unimpaired mental performance

With an emphasis from the aerospace community, research on the effects of heat on performance originated from proposals to prescribe upper limits of occupational exposure for unimpaired mental performance. In general, it is suspected that human performance deteriorates well before physiological limits. Wing (1965) was among the first to suspect that human performance deteriorates well before physiological limits and, as a result, documented upper thermal tolerance limits for unimpaired mental performance. The tolerance limits, which were well below the physiological tolerance limits, were based on the review of fourteen studies of the effects of ambient temperatures on mental performance. Wing's tolerance limits (Figure 1) used the Effective Temperature (ET) scale, an empirically determined index of the degree of warmth experienced by subjects when exposed to various combinations of ambient temperature, humidity and air movement.

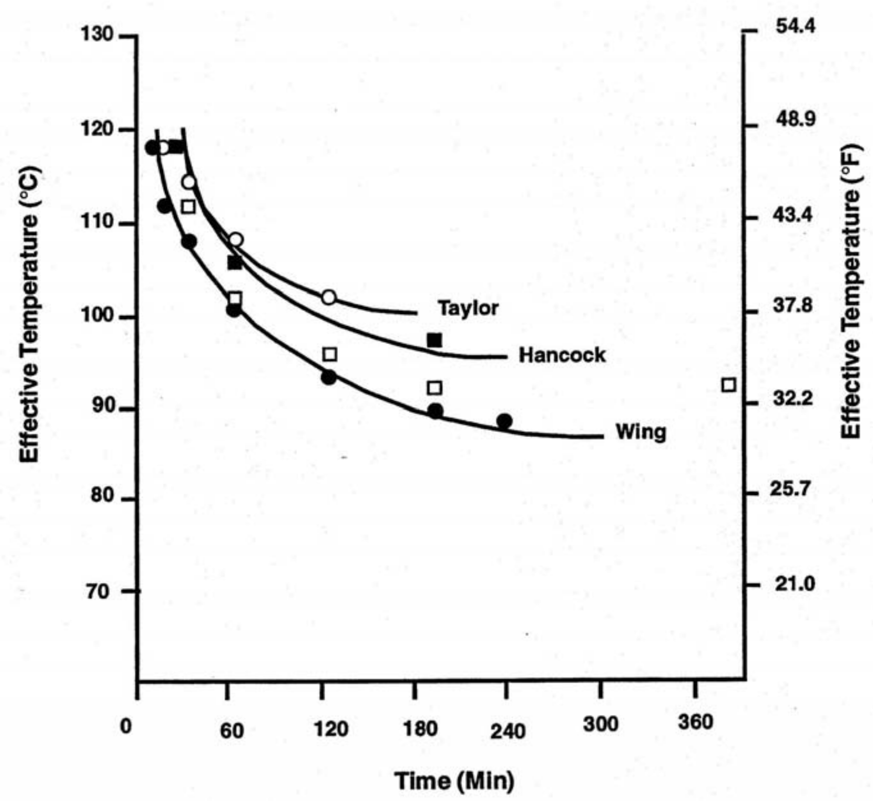

Figure 1: Exposure Limits generated by Wing (1965) and Hancock (1981b) (from Hancock & Vercruyssen, 1988)

In 1972 NIOSH prescribed upper limits of occupational exposure for unimpaired mental performance based on the research done by Wing (1965). In presenting this proposed upper limit for unimpaired mental performance, NIOSH modified the ET reported by Wing (1965) into corresponding WBGT (wet bulb globe temperature) units, although without any form of correction for radiant heat (Hancock & Vercruyssen, 1988). The limits proposed by NIOSH represented a general limit for all degrees of temperature acclimatization, all types of mental performance tasks, and all types of worker populations (Ramsey & Morrissey, 1978).

Ramsey and Morrissey (1978) reviewed and summarized a large amount of diverse data on human cognitive performance in heat and created predictive equations and isodecrement curves for mental, tracking, complex, reaction time and vigilance performance tasks. Figure 2 shows the isodecrement curve for vigilance tasks. For each task, the authors present a zero (0) isodecrement curve representing the boundary for no change in task performance, and a minus (-1) isodecrement curve, representing the boundary for definite significant decrements in task performance. They also produced two curves showing the combined tasks of mental-reaction time tasks and tracking-vigilance-complex tasks. The isodecrement curves allow the derivation of impaired performance boundaries for a certain time and temperature (in WBGT) for a variety of mental tasks.

Hancock (1981a) criticized the methodology used by Wing (1965) and the upper limits of unimpaired mental performance prescribed by NIOSH, and offered a reinterpretation of the conclusions reported by Wing (1965). This lead to further work by Hancock (1981b) in which a number of studies, reporting both decrement and no decrement, were reviewed. A synthesis of

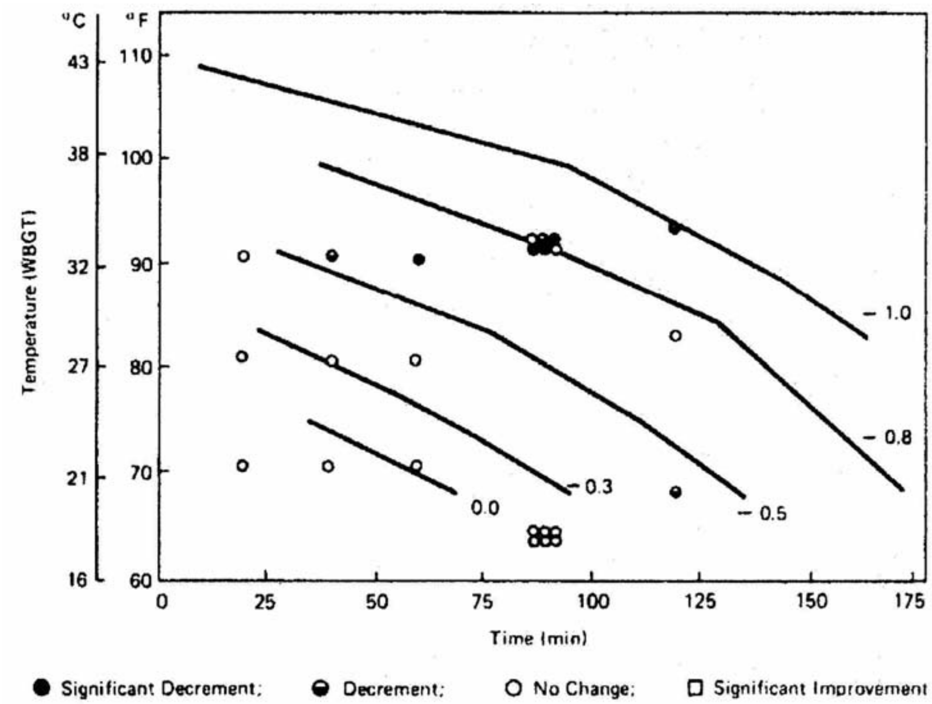

Figure 2: Isodecrement Curve for Vigilance Tasks (from Ramsey & Morrissey, 1978)

these studies revealed a set of distinct time-temperature tolerance limits for mental and cognitive skills (e.g. symbol matching, mental arithmetic, etc), tracking tasks and dual task performance (see Figure 1). All of these tasks required continuous rather than intermittent response. Hancock's tolerance limits were expressed using the ET scale, as opposed to WBGT. For each tolerance limit (i.e. tracking, dual task performance), Hancock reported an association between an increase in core temperature and the onset of impairment. For example, the performance limit for tracking performance suggests that the onset of impairment is associated with a core temperature increase of 0.88ºC/1.6°F per hour. Similarly, the performance limits for dual task performance and mental and cognitive skills are associated with a body core temperature increase of 0.22 ºC /0.4°F and 1.33 ºC /2.4°F per hour, respectively. Hancock (1981b) also included the performance limit for physiological performance in extreme heat, which is associated with a 1.67 ºC /3.0°F per hour rise in body core temperature. Hancock (1982) later noted that "although absolute values for the limit of completely efficient task performance are included for the three behavioural curves and the physiological tolerance curve, this is not to suggest that they are immutable thresholds. There are several factors which may affect the values which are proposed". Hancock (1982) identified that worker acclimatization, skill and response difficulty can all push the thresholds of performance.

The fact that performance in mental, vigilance and dual performance tasks can fluctuate according to factors such as worker acclimatization and skill, led Hancock and Vercruyssen (1988) to create three zones, as opposed to definite thresholds, which differentiate the limits of human behavioural efficiency in heat stress. These zones are illustrated in Figure 3. Hancock and Vercruyssen (1988)

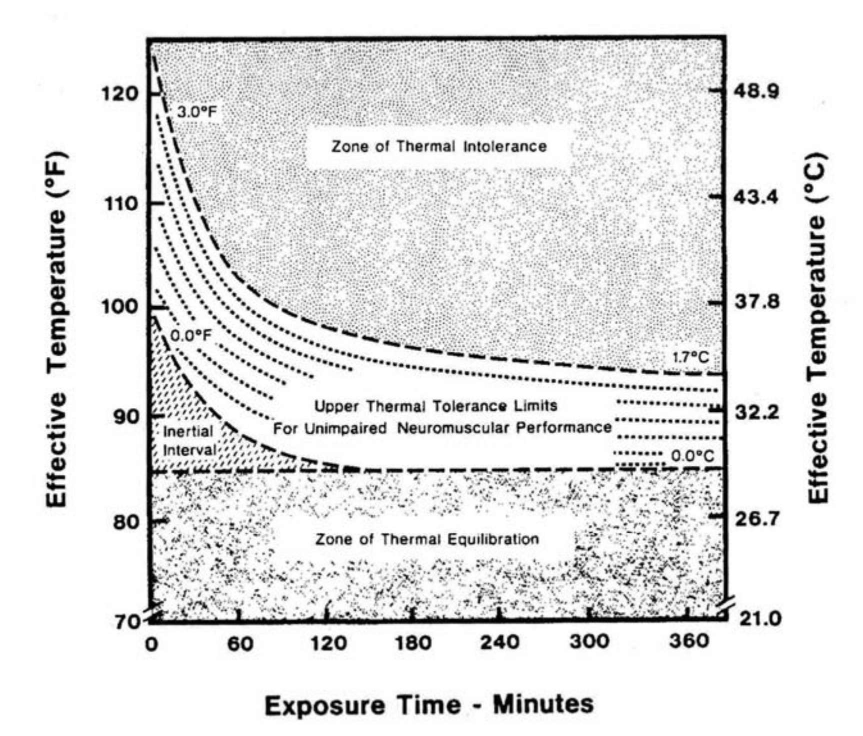

Figure 3: Zones of Thermal Tolerance (Hancock & Vercruyssen, 1988)

defined the zone of thermal equilibration as the area where cognitive performance should show little decrement while equilibrium is maintained. This zone is a region in which the core temperature remains largely stable in response to the ambient thermal surroundings. The combination of ambient temperature and exposure time are insufficient to perturb the thermal homeostasis of the exposed worker. The zone of thermal equilibration, which has a lower bound of 20.0ºC ET and an upper bound of 26.1ºC ET, describes the region where 94% of the population will be thermally comfortable while engaged in sedentary or near-sedentary activity (up to 180 kcal/h).

Hancock and Vercruyssen (1988) describe the zone of thermal intolerance as the time-temperature region in which there is a complete cessation of performance due to physiological failure. The lower boundary for this zone represents a 1.7ºC increase in core temperature per hour. Embedded within these two zones are isodecrement contours that describe the upper thermal tolerance limits for unimpaired neuromuscular performance. This zone refers to time-temperature values that result in a core temperature increase greater than 0ºC and less than 1.7ºC per hour. Ambient temperature values within this zone range from 26.1ºC ET to above 49ºC ET and depend upon task characteristics and exposure time. Finally, the inertial interval reflects the resistance of the body's core temperature to sudden changes. This secondary zone illustrates the fact that deep body temperature has an inertial lag and also has a tendency to elevate slightly with continued exposure. The inertial interval asymptotes at the upper bound of the equilibration zone, or a temperature of 30.0ºC ET.

In 1986, NIOSH released revised criteria for exposure limits to heat, based solely on human physiological response to thermal conditions. In response, Hancock (1987) questioned the premise that the aim of the criteria is diminished functional capacity, based on the fact that human psychological performance is more sensitive to heat stress than physiological performance. For similar reasons, Hancock (1987) also challenges the focus of the NIOSH revised criteria (1986) on physical, rather than cognitive or mental tasks.

Most recently, Hancock and Vasmatzidis (1998a) provide a new descriptive framework for human performance limits under heat stress. The framework involves an alternative representation of known exposure limit curves for different cognitive task categories. As shown in Figure 4, the horizontal axis is exposure time while the vertical axis is thermal intensity in ET. The vertical axis extends from the top at the upper boundary of tolerable conditions (i.e. 45.5°C/113.9°F ET), to the bottom, which represents the zone of equilibration (i.e. 29.4°C/84.9°F ET) (Hancock & Vercruyssen, 1988). This framework allows performance limit curves to be plotted as parallel lines, which are drawn from left to right in order of decreasing attentional demand. That is, the line on the far right illustrates the physiological tolerance ceiling. Following this (to the left) is the performance limit for simple mental tasks (Hancock, 1981b; Ramsey & Kwon, 1992). Next is the threshold for tasks requiring neuro-muscular coordination, followed by the performance limit for dual-tasks and finally, vigilance tasks. Clearly, vigilance is the most vulnerable to the effects of heat. The actual threshold for each of the above tasks is defined by the intercept value. Hancock & Vasmatzidis (1998a) describe that the major significance of this new descriptive framework is not the linearity of the plot, 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". That is, the thresholds for vigilance, dual-tasks, neuro-muscular coordination tasks and simple mental performance are a rate of change in body temperature of 0.055ºC/h, 0.22 ºC/h, 0.88 ºC/h and 1.32 ºC/h, respectively.

For a detailed account and comparison of the exposure limits and standards described above, refer to Hancock and Vasmatzidis (1998b).

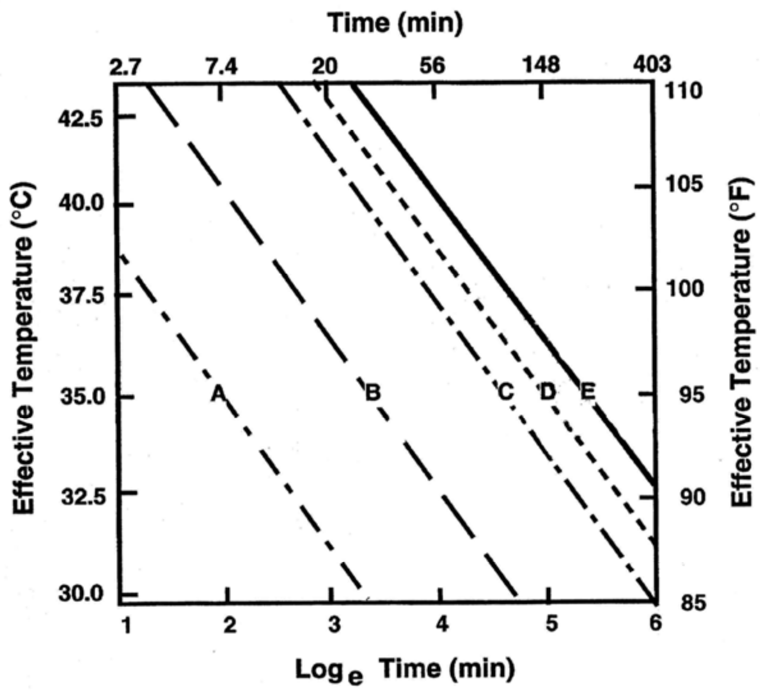

Figure 4: New Framework for Exposure Limits (from Hancock & Vasmatzidis, 1998a)

3.3. Physiological Indicators of Heat Strain that Significantly Affect Cognitive Performance

Although many studies have investigated the effect of increased ambient temperature on human performance, not all have addressed or calculated the thermal strain on the body, let alone independently manipulated thermal strain. Several researchers agree that one of the major limitations of research on the effect of heat on mental performance has been a failure to adequately define the thermal environment and the resultant thermal strain, as evidenced by core temperature (Tc) (Patterson et al., 1998; Nunneley et al., 1982). Specifically, Patterson et al (1998) note that:

> "much of the early psychological research did not account adequately for the impact of heat upon [core temperature]. For instance, numerous studies have only reported changes in [ambient temperature], or various forms of psychometric or effective thermal scales, and have implicitly assumed that changes in cognitive function were simply related to such conditions, rather than to the impact of the environment upon body temperatures. Since the capacity to tolerate heat is widely variable between people, and since cognitive function is less likely to be affected by [ambient temperature] than it is by its expression at the body core, then it is more relevant to relate cognitive function to Tc."

While there are many potential thermal strain measures including various approximations of core temperature (e.g. rectal, auditory canal), dehydration (quantified by loss of mass) and heart rate (HR), core temperature is the only metric that has been related to both physiological and cognitive performance (Hancock & Vercruyssen, 1988). The appropriateness of this is discussed later in this section.

Hancock & Vasmatzidis (2003) note that a trend has emerged among investigators attempting to explain the effects of heat stress on cognitive performance in a systematic way. Selected studies that have related heat stress (or thermal strain), as measured by core temperature, to cognitive performance are now presented.

Allnutt & Allan (1973) investigated the effects of core temperature elevation and thermal sensation on performance of a high-level reasoning task. It was determined that, when core temperature was increased to 38.7 ºC (by means of a climatic chamber), participants' speed of performance increased, but there were no changes in accuracy. In order to determine if the change in performance was attributable to an increase in body temperature or subjective discomfort, the authors eliminated the subjective discomfort by peripherally cooling the skin, without affecting the core temperature. The results suggested that the difference in performance is, in fact, attributable to an increase body core temperature rather than subjective discomfort.

More than a decade later, Holland et al. (1985) investigated the effects of raised body temperature on reasoning and memory. Participants' core temperature was raised from 36.88 ± 0.16 ºC to 38.97 ± 0.02 ºC by immersion in water at 41 ºC at which point they were tested on recall of memories registered an hour prior as well as immediate ability to recall digit spans forward or backward. They determined that an increase in core temperature did not significantly affect participants' long term or short-term memory.

Finally, as an "attempt to establish a relationship between deep body temperature and heat stress effects" (Hancock & Vasmatzidis, 2003; Hancock 1986) reinterpreted of a large number of studies and proposed three basic thermal states of the human body that define the efficiency of the operator exposed to thermal environments. The three thermal states are as follows:

1. Dynamic state – the imposed heat load results in an increase in deep body temperature away from a normative comfort level. In this state "heat storage in the body accumulates over time and [cognitive] performance breakdown will soon be observed." (Hancock & Vasmatzidis, 2003)
2. Hyperthermic state – the imposed heat load results in a constant elevated internal body temperature. Much of the available research suggests that vigilance performance improved in this state (Hancock & Vasmatzidis, 2003).
3. A state in which the external thermal load is not intense enough to cause an elevation in deep body temperature. In this state, vigilance performance remains essentially unaffected (Hancock & Vastmatzidis, 2003). The upper limit of ambient temperature exposure which results in no change in core temperature is 29.4ºC. Presumably, this limit would be dependent upon other factors such as acclimatization and clothing, but this is not explicitly stated by the authors.

A study by Patterson et al. (1998) demonstrates the latter state, in that a constant core temperature (i.e. no elevation in temperature) of at least 38ºC was imposed on all participants and was held for at least 1 hour yet participants' did not suffer impaired cognitive function. Specifically, they found no performance decrement on a visual attention (i.e. perception) task, spatial and temporal orientation (i.e. integration of attention, perception and memory), or a vigilance task. Therefore, results showed that visual perception, visual attention, spatial orientation and vigilance were all largely uninfluenced by heat strain.

Even within studies in which participants' core temperatures were documented and related to cognitive performance, some investigators have observed divergent results at similar core temperatures (Patterson et al., 1998). Patterson et al. (1998) state that, in such cases, the core temperature may have been similar but the air or skin temperatures were changing. This suggests that thermal strain may include a subjective component, as well as a quantifiable or objective, component (i.e. core temperature).

Ramsey and Kwon (1992) noted that decrements in perceptual motor performance in response to increased ambient temperature are not always consistent with fluctuations in body core temperature. First, in reviewing several studies on the effects of hot environments on perceptual motor performance, they note that even though core temperature has an inertial lag, cognitive performance degradation has been seen in instances with relatively short exposure times This may suggest that performance decrement is related not only to body core temperature. Second, Ramsey and Kwon (1992) note that core temperature has a tendency to elevate slightly with continued exposure which would suggest a continual deterioration in cognitive performance with prolonged exposure. This, however, has not been shown in studies of human performance in heat. As a result, Ramsey & Kwon (1992) propose that performance decrement may be better explained by body temperatures, as indicated by the head and blood temperature, than by the deep body temperature. Core body temperature is very resistant to change and therefore cognitive performance degradation may occur prior to a perceptible change in core temperature. Several researchers agree that temperatures of the head, hands, feet or skin may be a better predictor of performance effects because they are not as resistant to change (Allnutt & Allan, 1973; Ramsey & Kwon, 1992; Hancock & Vercruyssen, 1999).

A limited number of studies have investigated the relationship between temperature of the head, hands, feet or skin and human mental performance. Nunneley et al. (1982) investigated, among others, the effect of head temperature on cognitive performance and reaction time. Using a choice reaction task, the authors found no significant effect of head temperature on reaction time or number of errors. Nunneley et al., (1982) did report trends in terms of a decrease in reaction time and an increase in number of errors with increasing head temperature.

Hancock (1983) investigated the effects of an increase in head temperature upon performance of a simple mental task in order to further understanding about the relationship between selective head temperature variation and human performance. Hancock (1983) found that the mean number of simple arithmetic addition tasks attempted increased significantly when head temperature was elevated. However, there was no significant effect of thermal condition on number of errors (i.e. accuracy). Therefore, performance increased with increasing head temperature, but only with respect to speed.

3.4. How Physiological Indicators Affect Cognitive Performance

Hancock (1982) notes that "for over 3 decades psychologists have reported contradictory findings concerning human performance in elevated ambient temperature". Nunneley et al (1982) claim that the disparity in the literature on the effects of heat on performance is partly due to the use of a wide variety of tasks used by investigators with differing emphasis on speed and accuracy, cognitive and motor components, skill and motivation. However, Hancock (1982) also asserts that a major reason for contradictory findings is the tendency for investigators to control ambient conditions without documenting the physiological status of the participants.

As noted by Hancock (1982), the majority of studies on the effects of heat on cognitive performance have addressed the relationship between ambient temperature, rather than physiological indicators of thermal strain, and performance. Numerous papers have been published summarizing studies relating task performance and ambient temperature. One of the most comprehensive summaries was conducted by Grether (1973) in which five task categories were outlined: 1) time estimation, 2) reaction time, 3) vigilance and monitoring, 4) tracking, and 5) cognitive and other skills. Grether (1973) noted that an increase in time estimation as well as reaction time was directly related to ambient temperature increase. He also observed that vigilance performance was optimal at approximately 80ºF (26.7ºC) ET. For all other tasks (i.e. tracking, more complex cognitive tasks, etc.) there was a tendency toward performance decrement as ambient temperature exceeded 85ºF (29.4 ºC) ET. This temperature is also the point at which core temperature increases (Grether, 1973).

A more recent comprehensive review was conducted by Ramsey and Kwon (1992), in which the authors summarized over 150 studies where cognitive performance has been reported as a function of temperature, exposure time, and type of tasks. Based on the results of Ramsey and Morrissey (1978), they used two categories of task for their summary: 1) mental, very simple perceptual motor, reaction time, etc. 2) other perceptual motor tasks including tracking, vigilance, complex/dual, etc. In summary, the authors concluded that performance decrement in heat is not commonly observed in tasks belonging to the first category (i.e. mental, simple perceptual motor and reaction time tasks). They determined that there was, however, strong support for performance decrement in tracking, vigilance and dual tasks that tends to onset in the 30-33ºC WBGT range. Ramsey & Kwon (1992) also identified that this is the same temperature range as that associated with the onset of physiological heat stress for sedentary work.

However, Hancock (1986) contends that it is not simply elevated ambient temperature that affects one's cognitive performance; it is ambient temperature combined with exposure time that results in a change in deep body temperature that will lead to degradations in performance. Several researchers have attempted to determine the relationship between elevated deep body temperature (i.e. heat stress) and cognitive performance. Further, Hancock & Vasmatzidis (2003) note that one trend that has emerged in the literature on the effects of heat stress on cognitive performance is that heat affects cognitive performance differently, based on the type of cognitive task. That is, rather than focusing on cognitive performance as a whole, researchers now differentiate between tracking, vigilance, psychomotor, reaction time, simple mental and complex mental or dual task performance.

Grether (1973) summarizes a number of studies investigating the elevation of body temperature on time judgement and vigilance tasks. In terms of time judgement, research suggests that perceived time is decreased with increased body temperature, which can be manifested in several ways such as an increase in counting rate, tapping speed and estimation of time intervals (Grether, 1973). Grether also summarizes a study by Wilkinson et al. (1964) in which the authors found that, as body core temperature increased, participants' performance on a vigilance task improved but their performance on a complex secondary task (mental addition), decreased. In a more recent study, Ramzjou & Kjellberg (1992) found that heat stress adversely affected reaction time tasks. Specifically, the authors determined that, as core temperature increased, both mean and variability of reaction time in a serial reaction time task also increased. In summary, based on the above studies, it appears that an increase in body core temperature leads to a decrease in perceived time, which can be manifested as increased speed of performance and improved performance in vigilance tasks. An increased core temperature, however, appears to have an adverse effected on reaction time tasks.

The above investigations suggest that it is simply an increase in core temperature that causes an increment or decrement in cognitive performance. However, Hancock (1986) asserts that a significant breakdown in performance efficiency does not necessarily occur when core temperature is elevated, but when it is disturbed or changing; that is, when an individual's core temperature is in a dynamic, as opposed to a static, state. Johnson & Kobrick (2001) explain that the work of Wilkinson et al. (1964) supports Hancock's contention. They assessed auditory vigilance in participants who had stabilized at 1.4, 2.5 or 3.6°F (0.77, 1.38 or 1.98ºC) above pre-exposure body core temperature. When core temperatures increased by more than 1.4°F/0.77 ºC above pre-exposure temperature, vigilance performance improved. Hancock (1986) points out that the difference between this study and the others was the establishment of a static hyperthermic state that lacked the stress associated with the constant rise in body temperature. Thus, the data are in line with the notion that performance degradations resulting from heat exposure are associated with dynamic, rather than static, core temperature (Johnson & Kobrick, 2001). The results of Ramzjou & Kjellberg (1992) also support the notion that performance is related to the dynamic change in core temperature. They found that performance in a simple reaction time and serial choice reaction time task correlated with the rate of change, rather than the level of body core temperature.

Hancock (1982) conducted a synthesis of research that focuses on the effects of extreme thermal stress on performance in three types of tasks: 1) mental and cognitive tasks, 2) tracking tasks, and 3) complex or dual task performance. In particular, Hancock compared results from the three task categories with human physiological tolerance to high ambient temperatures. Using a mathematical function, outlined by Houghten and Yagloglou in 1923, Hancock equated performance limitations, expressed as a time-temperature limits (min-ET), to absolute rises in core temperature (see Figure 5). Hancock (1982) calculated that the time-temperature limit for unimpaired mental performance represents a rise in core temperature of 1.33 ºC/h. Likewise, the limit for tracking performance represents a rise of 0.88 ºC/h in core temperature, and the limit for complex or dual task performance represents a core temperature rise of 0.22 ºC/h. Interestingly, the threshold for physiological task performance is 1.67 ºC/h (Hancock, 1982). This reiterates the fact that, as ambient and body core temperature rises, cognitive performance decrements will be evident long before any evidence of physiological effects. A second observation that can be made is that the limit for unimpaired simple mental performance lies in close proximity to that of physiological tolerance. Finally, it is evident that complex or dual tasks, followed by vigilance tasks, are the least resistant to increases in ambient and core temperature.

Clearly, consideration must be given to why performance in some cognitive tasks is affected by thermal strain more than others. It has been suggested that "attentional resources demanded by the task are a key factor in determining performance breakdown and therefore attention-demanding tasks suffer earlier and more substantively than comparable but less attention-demanding tasks" (Hancock 1986a).

The mechanism by which an increase in core temperature results in either performance decrement or increment is not well understood. One potential explanation is that a rise in internal body temperature results in an increase in the rate of neural activity (Grether, 1973). This may explain an increase in performance in any task with a motor component such as a simple reaction time task or psychomotor task. A study by Hocking et al. (2001) supports this theory of increased neural activity, but also suggests that it may lead to improved performance in tasks without a motor component (i.e. memory and vigilance tasks). In their study, brain imaging showed changes in electrical activity in response to thermal stress during cognitive performance. Specifically, they found that brain electrical activity at single electrodes showed increased amplitude and decreased latency during both a spatial working memory task and a vigilance task, when performed in a thermal environment (Hocking et al., 2001).

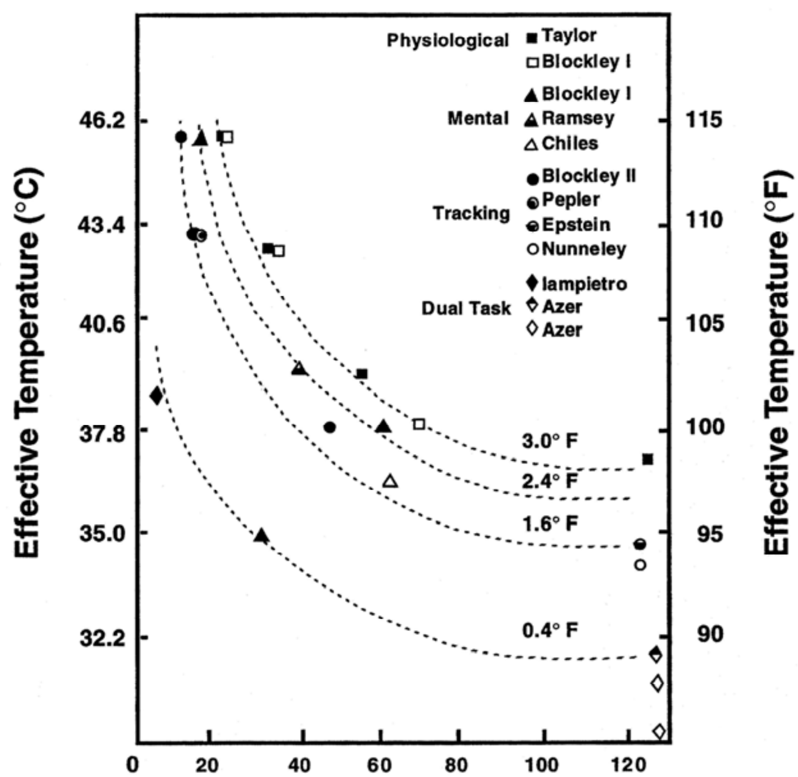

Figure 5: Exposure Limits With Corresponding Rate of Change of Core Temp (X-axis is exposure time in minutes) (from Hancock, 1982)

An alternative explanation of the effect of thermal strain on cognitive performance is that heat, as an environmental stress, competes for and may potential drain attentional resources. This notion is discussed in detail in section 4.1, in relation to Hancock's Maximal Adaptability Model (1989).

3.5. Other Factors That May Interact to Affect Cognitive Performance

Human performance in thermal environments may be affected not only by temperature level and exposure time, but also by several other factors including level of acclimatization, personal motivation, level of arousal (or fatigue), skill level, task difficulty, clothing and other characteristics of the individual, task and work environment. However, Ramsey and Kwon (1992) emphasize that much of the literature fails to identify or control these factors.

In a review of task performance in heat, Ramsey (1995) discusses the relationship between performance in a thermal environment and several factors including acclimatization, skill/training, clothing, and combined stressors. Although all of these factors may play an intervening role in human performance in heat, Hancock (1982) and Grether (1973) state that heat acclimation, hydration, and skill level are the most important factors. As a result, these three factors and their effects on human performance in thermal environments, are discussed in this section.

Acclimatization

Ramsey (1995) reports that human performance related to acclimatization is an area that is not well defined and not much of the reported literature specifies whether participants are acclimatized or unacclimatized. Several researchers allude to the fact that acclimatized subjects are likely to experience less performance decrement than non-acclimatized subjects (e.g. Wing, 1965), however few studies have actually included acclimatization as the main subject of investigation. Mallon and McCabe (1998) investigated the effectiveness of an acclimatization program on mitigating the effects of a heated environment on two cognitive tasks. The acclimatization program consisted of heat exposure 20 minutes a day for 10 consecutive days. Participants performed a letter rotation task as well as a scan and search task both during and after the acclimatization program. Results showed that performance of both tasks was significantly affected by heat exposure, and that acclimatized participants performed better at retest (post-acclimatization) than those not exposed to a heated environment (i.e. control group). That is, acclimatization positively affected cognitive performance.

In contrast, Curley and Hawkins (1983) investigated time estimation and performance (i.e. speed and accuracy) in a repeated acquisition task during a 10-day heat exposure acclimatization regime. Over the 10 days, participants' core temperature and heart rate decreased while sweat rate increased, indicating physiological acclimatization. However, mean performance on the repeated acquisition task remained impaired and time estimates were higher than during the first heat exposure, suggesting that these cognitive functions did not benefit from acclimatization.

Likewise, Patterson et al. (1998) failed to find any performance increment in acclimatized participants. The authors assessed the perceptual function, spatial orientation, temporal orientation and vigilance of participants during an acclimatization regime in which they were exposed to a thermal environment for 22 days. While the results showed that participants' physical capacity improved with heat acclimation, heat strain did not appear to affect perception, spatial and temporal orientation or attention. The authors concede that the cognitive function tests used may not have been sufficiently sensitive or that changes in cognitive function may only appear in more complex cognitive tasks.

For a good review of studies addressing heat acclimatization and its effects of cognitive performance, refer to Johnson & Kobrick, 2001.

Hydration

Patterson et al. (1998) note that "with very few exceptions, hydration state has frequently not been considered in experiments investigating heat and cognitive function". Of the research on cognitive performance in heat that has considered hydration state, the results are somewhat contradictory.

Sharma et al. (1986) used an 8-day heat acclimatization schedule, after which a dehydration condition was introduced and cognitive tests were administered. Specifically, substitution (routine symbol classification), concentration (working memory) and psychomotor (coordination) tests were used. The authors found that, although there was a progressive decrease in symbol classification scores with increasing levels of dehydration, there was no overall effect of dehydration. On the other hand, it was determined that dehydration had a significant effect on concentration and psychomotor tasks in that performance in a heated environment suffered with increasing dehydration.

Bradley & Higenbottam (2000) had participants exercise in a heated environment in either a dehydration (3-5% body weight) or euhydration condition. Following the exercise sessions, participants were administered tests of sustained attention, 4-choice reaction time, digital memory recall, digit symbol substitution and the multi-attribute task battery (MAT, containing tracking, communications, monitoring and resource management tasks). The results revealed performance impairment in tracking, resource management and sustained attention, as well as an increase in error rates in monitoring and choice reaction tasks. The authors report that these results suggest that dehydration may adversely affect tasks involving a motor component (tracking), purely cognitive tasks (monitoring and choice reaction time) as well vigilance type tasks. However, the authors reported that participants in the hypohydration condition reported an increased level of fatigue and decreased subjective alertness, thereby bringing into question the bearing that the method of inducing hypohydration (exercise in heat) may have had on the results.

In contrast, Leibowitz (1972) investigated the effects of heat stress on reaction time to centrally and peripherally presented stimuli. Participants were put through exercise sessions to induce heat stress. In the first set of sessions, body fluid were replaced while in the second set, fluids were not replaced (dehydration condition), imposing additional stress. The authors found that the effect of dehydration on peripheral or central reaction time was not significant.

Operator Skill

With respect to skill, research consistently suggests that workers who are skilled are more resistant to performance loss "unless they already have a high perceptual motor load which, in the addition of temperature, becomes an overload condition, and negatively affects performance" (Ramsey, 1995). Hancock (1982) reviewed several studies that investigate the effect of operator skill on performance in transient extreme heat. He concluded that task familiarity is beneficial in prolonging efficient performance in elevated environmental temperature and that skilled workers also appear less disturbed by concomitant thermal stress (Hancock, 1982).

Nunneley et al. (1978) also found that when operators are required to respond to novel or emergency situations (i.e. they have less skill) heat stress induces potentially dangerous performance degradation. As operator skill increases, more of the task becomes automated thereby requiring less control processes, and performance degradation is lower in thermal environments (Nunneley et al., 1978). Therefore, it could be conceived that an increase in operator skill may mitigate any decrement in cognitive performance due to heat stress.

Johnson and Kobrick (2001) synthesized data from validated heat stress studies and created a performance-heat exposure function for different skill or training levels. Figure 6 shows that "performance decrements are likely to be minimal when skill level is high, and considerable when skill level is medium or low" (Johnson & Kobrick, 2001).

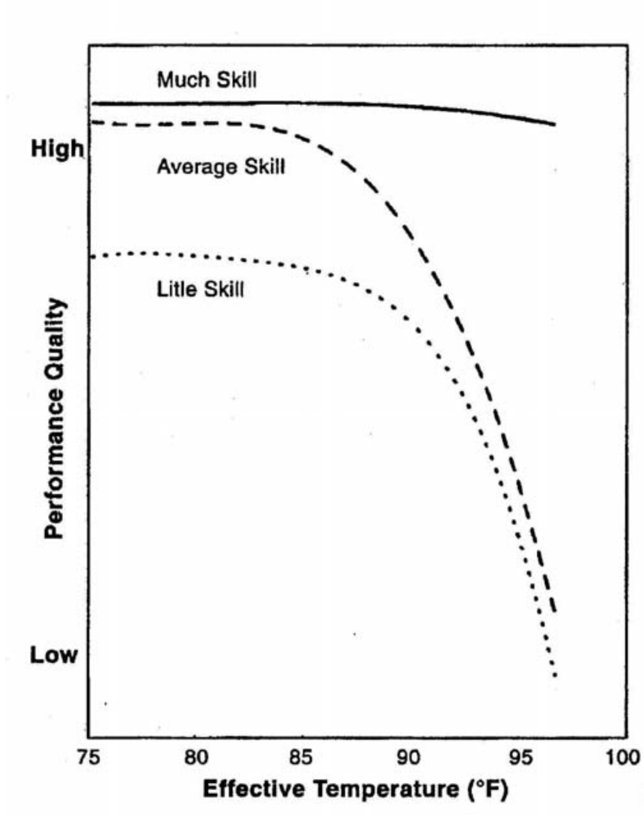

Figure 6: Performance Decrement and Skill Level (from Johnson & Kobrick, 2001)

3.6. Models Relating Heat Strain To Mental Performance

While there have been several representations of tolerance or exposure limits for unimpaired mental performance (see Section 3.2), these functions are based on the results of studies and are not theoretical in such a way that will allow the prediction of cognitive performance due to heat strain. It was determined that there are three models that have been conceived to explain and, more importantly predict, human cognitive performance in thermal environments. All of these models are based on theories that attempt to explain stress (e.g. heat) effects on human performance.

Arousal Theory

Currently, most widely accepted theoretical avenue for explaining stress effects on human performance is notion of behavioural arousal (Hancock, 1989). The arousal theory hypothesizes that the relationship between human performance and arousal (or stress) level is an inverted-U relationship, suggested by the Yerkes-Dodson Law (Yerkes & Dodson, 1908). This model (see Figure 7) suggests that at the lower end of the arousal scale (low stress), increasing stress by increasing arousal will increase performance. At higher levels of arousal, however, stress begins to produce attentional and memory difficulties that cause performance to decrease (Wickens & Hollands, 2001). A second characteristic of the Yerkes-Dodson Law is the optimum level of arousal is at a lower level for the more complex task (or the less skilled operator) than for the

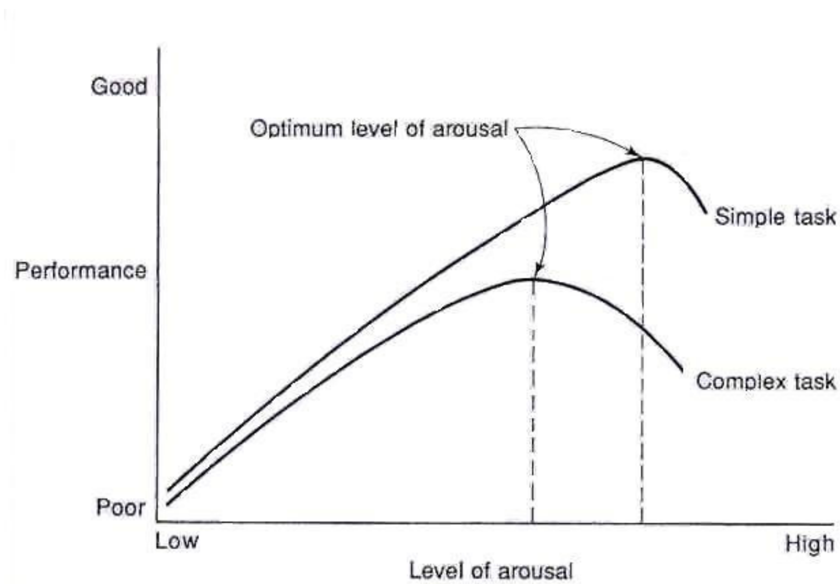

Figure 7: Yerkes Dodson Law (from Wickens & Hollands, 2001)

simpler task (or more skilled operator). That is, more simple tasks or more skilled operators can withstand more arousal/stress before performance is degraded. Likewise, more complex tasks, or less skilled operators, are more vulnerable to performance decrement caused by increasing arousal/stress. In other words, "for poorly learned tasks, performance is best when arousal is low" (Johnson & Kobrick, 2001).

In relating this theory to human cognitive performance in thermal environments, exposure to ambient heat is considered a stressor that increases arousal. Cognitive performance improves as arousal increases above a comfortable resting level (as can be caused by mild heat) but then degrades when arousal either drops below or rises above this optimal level, as in high ambient heat conditions. Grether (1973) has suggested that performance is optimal when ambient temperature is 80°F/26.7ºC ET, or just above the thermal comfort level.

Although the behavioural arousal theory seems to intuitively explain cognitive performance effects in thermal environments, it has been criticized for several reasons. First, Hancock (1989) asserted that it lacks predictive capability and questions its descriptive clarity and nature as a unitary construct (no result of hi/low stress). Also, Razmjou (1996) expressed concern that "the arousal theory accounts for performance effects only in relation to the level of nervous system activity and omits voluntary control that may be exerted in moderating stress effects".

Cognitive-Energetical Linear Stage Model Of Human Information Processing And Stress

Sanders asserts that "the aspecificity and unidimensionality of stress and arousal have been seriously challenged both from physiological and from behavioural research" (1983). In response, Sanders (1983) attempts to relate stress and arousal to a linear stage model of human information processing. It is referred to as a cognitive-energetical linear stage model of human information processing and stress. The aim of a linear stage model is a "description of information flow through the organism as a sequence of processing stages mediating the transformation from signals into responses" (Sanders, 1983).

Figure 8 illustrates Sanders' model of stress and human performance. Sanders (1983) explains that "in this model, stress arises because effort fails in correcting the effects of too high or too low a level of arousal, too high or too low a level of activation" or there may be "failures to supply sufficient energetical resources to reasoning and decision making". Stress arises whenever the effort mechanism is either seriously overloaded over a period of time, or falls short in accomplishing the necessary energetical adjustments to maintain stress level. It is at this point that that performance becomes affected.

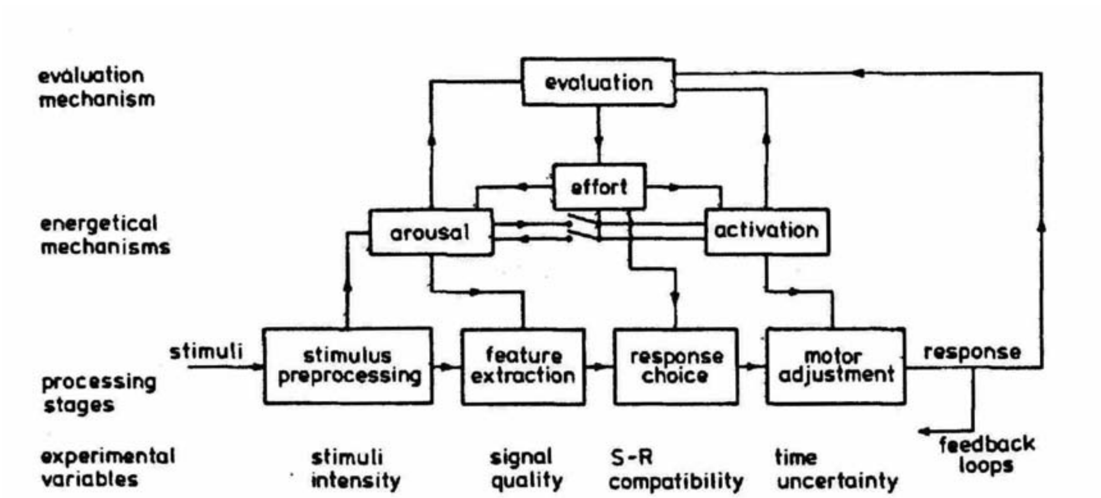

Figure 8: Cognitive-Energetical Linear Stage Model of Human Information Processing and Stress (from Sanders, 1983)

Maximal Adaptability Model (Hancock, 1989)

As previously mentioned, several researchers recognized the lack of predictive capability and other limitations associated with the Arousal Theory. As a result, Hancock (1989) examined the effects of stress on sustained attention with the goal of providing the steps toward a dynamic model of stress and operator performance.

After reviewing numerous studies of vigilance (or sustained attention) performance in thermal environments, Hancock (1989) summarized the patterns of vigilance performance under heat stress. Specifically, he noted that vigilance performance is unaffected with no variation in core temperature and is facilitated when the subject is in a static hyperthermic state (i.e. elevated but static core temperature). Further, performance in vigilance tasks is degraded as thermal homeostasis is disturbed (i.e. core temperature is in state of change).

From this knowledge, Hancock (1989) created a model, called the Maximal Adaptability Model (see Figure 8). This model is based on the concept of adaptability in both physiological and psychological terms. That is, humans have both physiological and psychological compensatory mechanisms that allow us to adapt to increased stress (i.e. heat) without affecting performance, but only to a certain point. The stage during which physiological or psychological compensatory

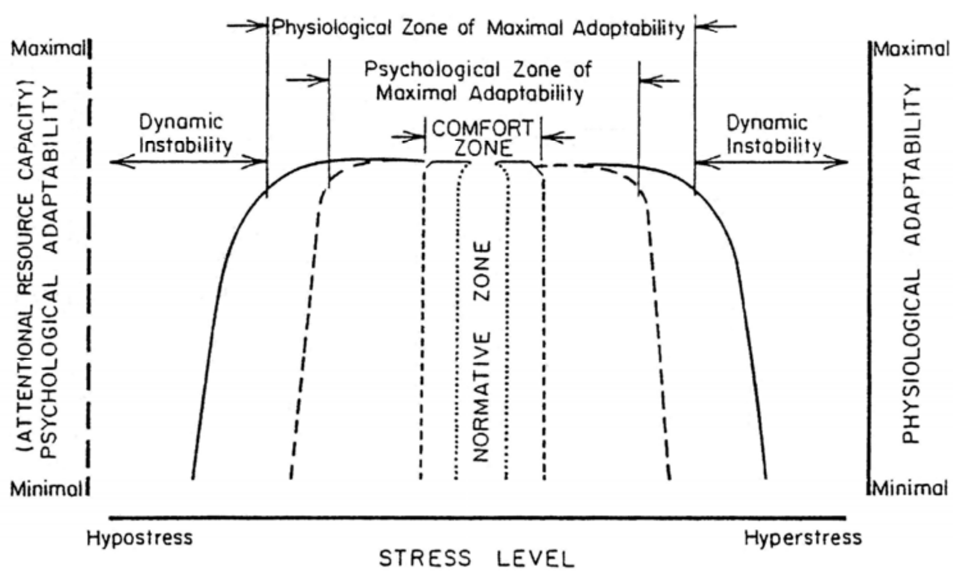

Figure 9: Maximal Adaptability Model (from Hancock, 1989)

mechanisms are active and successfully maintaining performance efficiency is referred to by Hancock as "dynamic stability". The point at which these compensatory mechanisms can no longer maintain performance is referred to as the transition to "dynamic instability". Hancock (1989) notes that "in the present form of the model, psychological adaptability is closely tied to contemporary notions of operator attentional resource capacity, whereas physiological adaptability is related to traditional representations of homeostatic adjustment. Therefore, with respect to psychological performance, this model assumes that heat adversely affects vigilance performance by competing for and eventually draining attentional resources, which are required for optimal performance (Hancock & Vasmatzidis, 2003).

Upon inspection of Figure 9, it is evident that there are three modes of operation in the model; one in which the input stress (e.g. heat) does not disturb the physiological or psychological state of the operator, a second in which physiological or psychological compensatory mechanisms are active to preserve performance, and a third in which adaptive or compensatory mechanisms become overloaded and performance is degraded. The "normative zone" represents the region in which compensatory activity is minimized because the level of input (i.e. stress) is not sufficient to create a dynamic response. The "comfort zone" represents a region of comfort desired by the operator. The "psychological zone of maximal adaptability" is the region in which stress (i.e. heat) levels create a dynamic response (i.e. compete for attentional resources), but do not adversely affect psychological performance because of compensatory mechanisms. The "physiological zone of maximal adaptability" is similar to that of the psychological zone in that compensatory mechanisms prevent changes in physiological state that affect performance. It is important to note that the physiological zone is larger than the psychological zone, indicating that psychological performance degrades prior to physiological performance as a result of increased levels of stress. Finally, the zones of "dynamic instability" represent the region in which the level of stress is high enough that the compensatory mechanisms are no longer able to maintain system stability (physiological or psychological). That is, performance degrades as a result of input stress, which can increase either through change in intensity, prolongation of exposure time, or both in combination.

The model also illustrates that temperature can have a bi-directional influence in that too little (hypostress) or too much heat (hyperstress) is stressful.

In summary, the model suggests that "minor levels of input stress are readily absorbed by adaptive capability; they do not disturb steady-state functioning and so are not reflected as output stress, manifest in change of behaviour" (Hancock & Vasmatzidis, 2003).

Hancock (1989) discusses the limitations as well as the advantages of the Model of Maximal Adaptability. He lists the following limitations:

1. "[The model] does not provide complete solutions to numerous problems posed by the effect of both single and multivariate sources of stress on operator performance. Particular concern is quantitative identification of the numerous factors", and,
2. "Prediction implies a knowledge of the goals and skills of the individual which remain to be adequately addressed".

Nevertheless, he lists the following as advantages of the model:

1. The model was generated specifically for stress effects;
2. The model can be extended to combinations of multiple tasks as well as numerous sources of stress (e.g. noise);
3. It provides insights into failure in operator performance under the influences of stress;
4. It "provides testable propositions that, if confirmed, would provide the predictive capacity that is absent in the behavioural arousal conceptualization", and,
5. It suggests that physiological and cognitive response strategies work together as a single response strategy to stress.

3.7. Sources of data for developing or validating quantitative models of heat strain and mental performance

Very little research on the effects of heat stress on cognitive performance have documented, let alone independently manipulated, measures of heat strain. Consequently there are very few sources of data that directly relate heat strain indicators, such as core temperature and heart rate, to cognitive performance. In general, the most valuable sources of data for developing or validating quantitative models of heat strain and mental performance are from the work of Hancock (1982, 1986, 1998a).

Hancock (1982) examined human performance limitations in various cognitive task categories in thermal conditions. Upon reviewing numerous studies, Hancock (1982) concluded that performance decrement might be apparent in mental and cognitive skills, tracking and dual task performance as ambient temperature exceeds 85ºF (29.44 ºC) ET. The proposed thresholds of performance impairment for the above tasks were then equated with rises in deep body temperature. In summary, it was calculated that the time-temperature limit for unimpaired mental performance (i.e. mental arithmetic tasks) represents a rise in core temperature of 1.33 ºC/h. For tracking performance, the limit is 0.88 ºC/h and for complex or dual task performance it is 0.22 ºC/h.

Hancock (1986) conducted a comprehensive review of the effects of the thermal environment of sustained attention, or vigilance. In this review, he described in detail several studies relating core temperature to several factors including response latency, signal detection or recognition, number of errors and types of errors (e.g. omission) for both auditory and visual vigilance tasks. This review applies to exposure of both heat and cold, but is limited to vigilance tasks only.

More recently, Hancock & Vasmatzidis (1998a) provided a new framework for setting performance limits in thermal environments. In this framework, known exposure limits for various types of cognitive tasks are plotted in such a way that the actual threshold for each type of task is defined by the intercept value and each threshold describes a particular dynamic rise in deep body temperature that corresponds to the performance limit for that task. In summary, the authors calculated that the respective thresholds for vigilance, dual-tasks, neuro-muscular coordination tasks and simple mental performance are 0.055ºC, 0.22 ºC, 0.88 ºC and 1.32 ºC increases in body temperature per hour.

The research outlined above directly relates dynamic increases in core temperature to performance in different types of cognitive tasks and is therefore the most valuable source of data for developing or validating quantitative models of heat strain and mental performance. However, there are certain limitations relating to the generalizability and applicability of the results that should be noted. First, Hancock (1982, 1998a) based his limits for unimpaired mental performance on studies that involved sedentary tasks only. Consequently the proposed threshold limits apply to sedentary tasks, which are unlikely to be representative of real-world tasks in which cognitive performance decrements would be of particular concern (i.e. high-risk tasks such as fire fighting, war fighting, etc.). Second, the threshold limits generated by Hancock (1982, 1998a) are expressed in rate of change of core temperature. While this may be a reliable indicator of thermal strain, it is only one indicator and it may not be the most feasible in an applied setting, nor may it be the most appropriate indicator as it is seldom an independent variable in experiments. That is, it is likely easier to quantify other physiological indicators, such as heart rate, in certain experimental environments.

4. Conclusions

The objective of this literature review was to identify the quantitative relationships among thermal strain factors that significantly effect mental performance.

It was determined that very few attempts have been made to directly link physiological indicators of thermal strain and cognitive performance. Core temperature is the primary variable that has been controlled or independently manipulated in work investigating the effects of thermal strain on cognitive performance, although these investigations are uncommon.

The literature review revealed three qualitative models of cognitive performance effects of thermal strain. No quantitative models were found, and unfortunately, minimal data was identified that could be used in the creation of quantitative models.

In future research there is a need to isolate factors that can interact with heat and its effect on human performance. Continued research on the contribution of acclimatization, hydration level, operator skill, clothing, etc. is imperative in order to isolate the effects of heat on cognitive performance.

Finally, existing research, upon which exposure limits is based, applies to sedentary tasks only. As a result, the generalizability of the results and exposure limits are questionable. Hence, there remains a need for research that is applicable to real-world tasks in which cognitive performance is crucial, such as fire fighting or military operations.

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14. ABSTRACT

(U) This report reviews the literature on cognitive effects of thermal strain. Early research focused on the relationship between ambient temperature and various cognitive tasks including sensory, vigilance, reaction time, etc. More recent work has focused on the prescription of tolerance limits as well as attempts to generate a conceptual model to explain and predict the effects of heat on cognitive performance.
In general, it was found that investigations relating thermal strain indicators, such as core temperature, to cognitive performance are sparse; the majority control and manipulate ambient temperature. Likewise, the isolation of other factors that may interact with heat to affect cognitive performance is infrequent. This report presents findings on the interaction effects of acclimatization, hydration level and operator skill, on human cognitive performance.
Recent attempts have been made to conceptually model the effects of stress (i.e. heat) on human performance. In this review, three qualitative models are discussed and compared. The literature review failed to uncover any quantitative models.
Finally, conclusions are made with respect to the need for research that is applicable to real−world, high−risk tasks in which cognitive performance is crucial such as fire fighting or military operations.

(U) Le présent rapport passe en revue la littérature portant sur les effets cognitifs de la contrainte thermique. Les premières recherches étaient axées sur le lien entre la température ambiante et diverses tâches cognitives, y compris les tâches sensorielles, la vigilance, le temps de réaction, etc. Les travaux plus récents ont été concentrés sur la prescription de limites de tolérance ainsi que sur les tentatives visant à produire un modèle conceptuel pour expliquer et prévoir les effets de la chaleur sur le rendement cognitif.
De façon générale, on a constaté que les recherches établissant un lien entre les indicateurs de la contrainte thermique, comme la température centrale, et le rendement cognitif sont rares; la majorité d entre elles consistent à contrôler et à manipuler la température ambiante. De la même façon, il est rare que les chercheurs aient tenté d isoler les autres facteurs pouvant interagir avec la chaleur pour influer sur le rendement cognitif. Ce rapport présente les résultats d études sur les effets sur le rendement cognitif de l interaction de l acclimatation, du niveau d hydratation et des compétences de l opérateur.
Récemment, on a tenté d élaborer un modèle conceptuel des effets du stress (c.ÓàÓd. de la chaleur) sur le rendement humain. Dans la présente analyse documentaire, on décrit et on compare trois modèles qualitatifs. L analyse documentaire n a pas permis de mettre au jour des modèles quantitatifs.
Enfin, on tire des conclusions quant à la nécessité d effectuer des études applicables à des tâches à risque élevé réelles, pour lesquelles le rendement cognitif est crucial, telles les opérations de lutte contre l incendie ou les opérations militaires.

15. KEYWORDS, DESCRIPTORS or IDENTIFIERS

(U) thermal strain; heat strain; cognition; mental performance