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Sustained Attention Under Thermal Stress

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This article reviews the effects of the thermal environment on vigilance. A reinterpretation of early and contemporary studies contradicts the existing notion that vigilance is facilitated in ambient temperatures that exceed a comfortable level. Rather, performance is degraded as thermal homeostasis of the observer is disturbed. Significant breakdown in capability becomes manifest with measurable perturbation to deep body temperature. This assertion requires that conditions induce a *dynamic* change, as performance is unaffected with no variation in deep body temperature and is facilitated when the observer is established in a *static* hyperthermic state. An attentional account of this phenomenon is offered, which contrasts with previous arousal explanations.

A common strategy in experimental psychology is to study a particular phenomenon by examining response under the effects of some perturbation or adverse condition. This tactic has the added benefit of also providing information about the action of some specific stressor or group of stressors on human capabilities. Through this approach, a unitary theoretical account of stress and performance has come to prominence, in that the single mechanism of arousal has been postulated to subsume the action of many different stressors on a wide variety of abilities. Recent theoretical and empirical insights appear to belie such a simple overall interpretation (e.g., Hancock, 1984b; Hockey & Hamilton, 1983), although it should be noted that the disparate action of differing stressors was first recognized over two decades ago (Broadbent, 1963).

More thorough understanding of the action of stress may be derived from the examination of evidence concerning one particular type of performance and how it varies under the impact of one specific stressor (e.g., Hancock, 1981, 1982). Using this tactic, I examine both early and contemporary evidence concerning one order of performance, that of sustained attention or vigilance, and its variation under the impact of differing thermal environments. Previous views concerning the change in vigilance capability under hot and cold conditions are not affirmed, and the preponderance of experimental evidence suggests a different perspective from which to view the action of thermal stress and, potentially, a wide variety of other stressors.

The genesis of coherent study of the phenomena of vigilance is attributed appropriately to the now classic work of Mackworth (1950). Although he acknowledged a debt to Head (1926) in relation to the origin of the term, Mackworth's empirical observations provided the fundamental foundation on which current research is built (see Davies & Parasuraman, 1982; Davies & Tune, 1970; Mackie, 1977; Warm, 1984). Among Mackworth's initial experiments was a practical examination of the effect of environmental temperature on watchkeeping ability. His findings suggested that performance was optimized at an ambient temperature exceeding that of typical thermal comfort. This observation was replicated by Pepler (1958), who affirmed an inverted U-shaped relation between performance capability and the level of thermal stress. Despite subsequent experimental work, current assertions concerning sustenance of attention in heat and cold are essentially derived from these seminal investigations. Thus, Davies and Tune (1970) indicated that capability in general was vulnerable to thermal effects, whereas latterly, Davies and Parasuraman (1982) concluded that mild heat facilitates performance, and cold impairs monitoring capability.

Grether (1973) was more specific in stating that optimal vigilance occurs at 80 °F (26.7 °C) on the effective temperature (ET) scale,[1] which is an index of the thermal environment calculated from measures of dry-bulb temperature, relative humidity, and air velocity (Houghten & Yagloglou, 1923). Grether's value was derived from a mean of the two conditions noted by Mackworth (1950) and Pepler (1958) as those in which superior performance could be observed. The resultant inverted U-shaped function has been used as support for an arousal account of vigilance performance under thermal stress that remains the only comprehensive explanatory construct of performance variations noted (cf. Hancock, 1984b; Poulton, 1977). One requirement for a unitary account of vigilance under thermal stress is the ability to predict the change in performance as reported by various existing studies. The arousal position accomplishes this by identifying differing arousal states. These states are dependent on reaction to the level of the particular stressor at hand. Increase in performance level is induced by elevation of arousal, whereas

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[1] All temperature values are expressed in both Farenheit and Centigrade with the first figure being as in the original report referenced with its scalar equivalent following in parentheses.

depression of arousal reduces performance efficiency (Poulton, 1977).

The present approach distinguishes between the *thermal* states of the observer involved. In the following sections, three basic thermal states are presented. The first is a dynamic state in which, because of the environmental thermal load, the participant experiences a constant change in deep body temperature away from both a normative level and a steady state. The second is an elevated level of body temperature, or hyperthermic state, with the distinction that the subject has been stabilized in such a condition. Parenthetically, there are currently no corresponding studies that report on performance under equivalent stabilized hypothermic states. In the third condition the deep body temperature of the observer does not vary despite the change in ambient environment. These three states are distinguished for both hot and cold conditions. The synthesis of evidence that follows is based on this tripartite differentiation and is followed by a discussion that examines previous and current theoretical proposals that might account for the results presented.

Experimental Evidence: Sustained Attention Under Thermal Stress

Heat: Dynamic Change in Deep Body Temperature Degrades Performance

In Mackworth's (1950) original experiment, subjects were required to monitor a hand on a clock face that made sequential clockwise jumps at 1-s intervals. A full revolution of the hand consisted of 100 such jumps and the critical signal for response was a temporally irregular double jump of the clock hand. Although immediate response was requested, subjects were also instructed to respond if they recalled critical signals to which they had not responded one or more jumps before. A between-subjects design was used to investigate the effect of four different heat conditions. Results for response latency, signal omission, and a combined median response time performance metric indicated optimum efficiency at 79 °F (26 °C) ET compared with a lower, 70 °F (21 °C) ET, and two higher, 87.5 °F (31 °C) and 97 °F (36 °C) ET, conditions. Performance capability declined during the second hour on watch and this propensity, commonly termed the *vigilance decrement function,* was exacerbated by increasing the heat above the optimum 79 °F ET level.

There are two important elements of this foundational work that have generally escaped notice. First, the optimal performance condition was the only one of the four investigated that did not cause a dynamic change in the deep body temperatures of the participants. Mackworth indicated that his acclimatized subjects performed the sedentary task wearing only gym shorts. They were exposed to an air movement of 100 ft/min and experienced an average 1.0 °F (0.6 °C) fall in deep body temperature during the 2-hr exposure at 70 °F (21 °C) ET. It has been indicated that exposures above 85 °F (29.4 °C) ET result in a noncompensable rise in deep body temperature, where absolute rate of rise is dependent on severity of the heat and length of exposure (e.g., Grether, 1973; Hancock, 1982; Houghten & Yagloglou, 1923, Figure 5; Lind, 1963). The two highest heat stress conditions in Mackworth's experiment, that is, 31 °C and 36 °C ET, exceeded this threshold value. Mackworth affirmed body temperature increases by reporting elevated rectal temperatures for individuals at the termination of the exposure. These observations suggest that the dynamic perturbation to the deep body temperature of the subject may be an important element in performance variation.

The second tendency that Mackworth noted was that the decrement in vigilance efficiency due to the stress was palliated by the experience level of the subject on watch (see also Hancock, in press). This trend was interactive with both increase in ambient temperature and time on watch, and indicated that the more experienced the subject at the task at hand, the less they were disturbed by the introduction of the thermal stressor. It is salutary to note that this seminal work is, in many ways, still the most comprehensive empirical examination of sustained attention under thermal stress to date.

A subsequent study by Pepler (1953) is usually projected as a replication that provides direct support for the position advanced by Mackworth. This is an oversimplification. Pepler (1953) conducted two experiments on the identical clock test but with participants who were naturally acclimatized to heat through habitation in a tropical locality. Three ambient conditions, 67 °F (19.4 °C), 82 °F (27.8 °C), and 92 °F (33.3 °C) ET were used. In an initial experiment, after eliminating the results from six subjects whose data were confounded by artifactual contamination, Pepler found signal omission was greatest and performance poorest at the median 82 °F (27.8 °C) ET condition. These data were in direct disagreement with the initial findings of Mackworth some 7 years earlier. Pepler claimed that the irregularity of experimental exposures and the equivalency of the median condition to the ambient tropical climate in which the work was conducted were mainly responsible for the apparently contradictory results.

There is an alternate account of these data that is founded on two assumptions. The first assumption is the existence of a practice effect on the vigilance task used. This appears reasonable, given Pepler's observation of a significant Performance × Days effect in a second, more thorough, experiment although a null effect for practice on the clock task has been reported by Carpenter (1946). The second assumption is that performance motivation is reduced by testing over a period of days with irregular exposures. Again, Pepler provided subjects' evaluative responses, which indicate that such is the case. These assumptions suggest that performance is at a maximum toward the middle of any individual's testing regimen, when initial practice has improved capability while motivation to perform has not been extinguished. Empirical data from Pepler's subjects indicate that more than 50% of the 18 subjects exhibited this particular trend. In this experiment, Pepler took care to counterbalance for this order effect by using four 6 × 6 Latin square designs for the 24 subjects tested. However, in eliminating the results for six subjects for legitimate artifacts, that is, two subjects for sleeping on watch and four for guessing the algorithm for critical signal appearance, Pepler inadvertently eliminated a disproportionate number of occasions in which the intermediate 82 °F (27.8 °C) ET condition occurred in the central testing position. In the 18 subjects analyzed subsequently, only 3, instead of 6, performed this condition while in the middle phase of their testing regimen. This might be responsible for the result of elevated signal omission at the median temperature. In consequence, Pepler's initial contrasting result may be due to a problem with subject elimination, rather than equivalence of local thermal condition to one experimental temperature, as he suggested.

This brief précis of Pepler's first experiment does not exhaust all the problems concerning the contradictory finding of performance diminution at the middle test temperature. For example, not all subjects exhibited the tendency toward optimum performance in the middle of the testing regimen. Pepler achieved the highest 92 °F (33.3 °C) ET condition by two dry bulb–wet bulb combinations with the subsequent addition of local air movement. Consequently, each subject performed on six occasions rather than three as the number of temperatures suggest. Also, because of experimental procedures, subjects were not tested at the same time of day for each temperature, a factor that has been noted as influential in performance capability (e.g., Colquhoun, 1960; Craig, Wilkinson, & Colquhoun, 1981). In sum, the problems outlined above appear to justify Pepler's decision to reject the results of his initial experiment, which do not appear subsequently in the final published report (cf. Pepler, 1953, 1958).

The second experiment reported by Pepler (1953) controlled for many of the extraneous variables of the first experiment. Eighteen participants were tested at the identical thermal conditions used in the first experiment, but at the same time of day for three consecutive days. A Latin square design, without elimination of subjects, allowed for control of an order effect (but see Poulton, 1973). The results for incidence of signal omission affirmed those of Mackworth (1950) by indicating optimal performance at the median temperature value, although again the tendency toward facilitation at the central condition might be due to a range effect (Poulton, 1973).

Consistent with Mackworth's findings, the physiological data showed that the two extremes of temperature also caused the greatest perturbation of deep body temperature. Data from these two foundational experiments allow two interpretations. The first, which is based on an arousal position, emphasizes the increase in vigilance in ambient temperatures that exceed a comfortable level (see Davies & Parasuraman, 1982; Grether, 1973). However, a second interpretation is that vigilance performance is depressed in conditions sufficient to induce a dynamic and noncompensable change in the deep body temperature of the observer. There is a considerable body of evidence suggesting that the latter proposition describes, more veridically, the limitation of human sustained attention in heat and cold. This evidence is explored in further detail below.

Although Mackworth's investigation is identified as originating work on vigilance, a contemporary study by Viteles and Smith (1946) examined a similar performance task in the presence of heat and noise. Subjects inspected pairs of numerical series and checked those pairs that contained identical digits. The task duration was 30 min and it was embedded in an exposure totaling 6 hr. The task was performed at 73 °F (22.8 °C), 80 °F (26.7 °C), and 87 °F (30.6 °C) ET, but with a constant noise background of 72 dB on the A-weighted scale. Performance for the entire group of subjects was scored on the basis of percentage output and percentage error. Although error remained essentially constant for this task, percentage output dropped with increasing temperature. These data are presented in Figure 1.

Significant decrement occurred at the highest ET condition when compared with the two lower temperatures. The latter 87

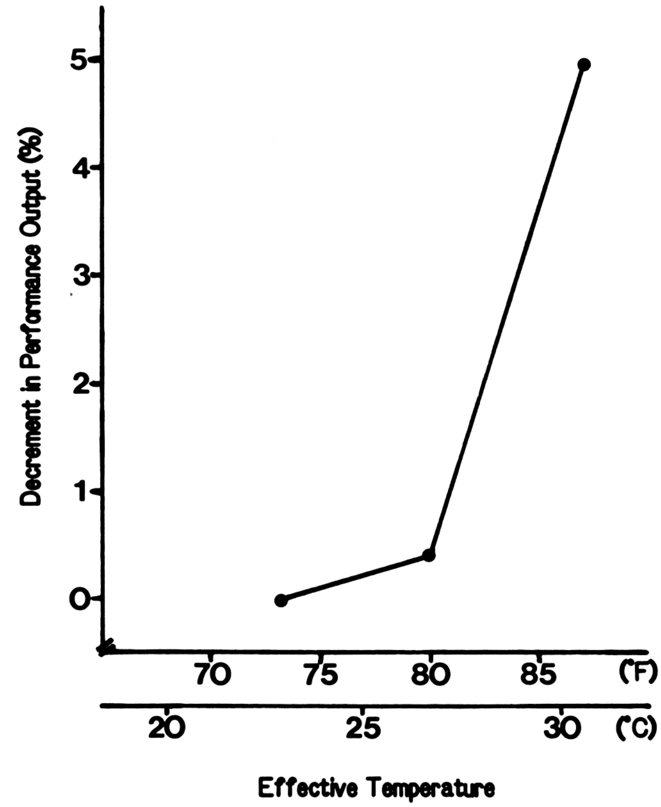

Figure 1. Decrement in performance output versus environmental effective temperature. Performance in the presence of a constant 72-dB noise stressor. (Data from Viteles & Smith, 1946.)

°F (30.6 °C) ET condition exceeded the 85 °F (29.4 °C) ET threshold value at which complete bodily compensation to the increased heat ceases to be tenable (Hancock, 1982). Viteles and Smith (1946) confirmed this by reporting that oral temperature exhibited a most marked increase in this condition, with an elevation of 1.4 °F (0.8 °C) on average for the participants tested. Despite the potential confounding effect of noise introduction, an effect that is not thought to be great (Hancock & Pierce, 1985), these early data appear to support the notion that vigilance is reduced in conditions that perturb individual thermophysiological state.

Although the work of Mackworth and Pepler is generally well recognized, the experiments of Fraser (1957) have received little recognition. This is the case despite the fact that Fraser is probably the first to introduce the notion of event rate as a potential factor in vigilance efficiency. In his first, practically oriented investigation, the monitoring task was introduced after the establishment of the overall experimental protocol, which was a large-scale investigation of the capability of mine personnel. As a result, Fraser's task took only 15 min to complete and was undertaken prior to and immediately after heat exposure. Subjects monitored circles of light, displayed for 400 ms and presented at the rate of one every 2 s. A critical signal was constituted by the appearance of a larger ratio diameter circle in the ratio of 3:2 to nonsignal stimuli. There were 10 such signals during each session.

This experiment had many problems, which cloud any simple interpretations that might be drawn. First and foremost, the length of exposure was inversely related to the severity of the heat imposed. Individual exposures were halted if a preset physiological criterion deep body temperature of 101.8 °F (38.8 °C) was exceeded, or if the subject experienced excessive discomfort. Second, the task was interpolated with other performance measures and taken prior to and after, but not during, the heat stress exposure. Third, different personnel collected the experimental data, and problems were also noted with the test equipment. In terms of incidence of missed signals, Fraser's data indicated a progressive increase in the number of omitted responses up to the middle temperature of the five investigated. However, above this level, signal omission decreased, but these latter conditions are those that Fraser specifically noted as being curtailed because of violations of physiological and subjective tolerance.

In response to these limitations, a subsequent experiment was conducted under laboratory rather than field conditions. In a preexposure control session, only 2 of a possible 720 signals were missed by the 24 participants who each undertook three 10-min periods on watch. However, as the level of heat stress increased, the number of missed signals ascended to 2.8% at approximately 100 °F (37.8 °C) ET. Even using the brief 10-min periods on watch after heat stress, there was a significant decrement when performance was compared after the first hour with that after the second hour of heat exposure. Unfortunately, the interactive effect of heat against performance in a more comfortable thermal condition was apparently not examined. Overall, Fraser's results indicated that heat affects vigilance to brief but rapid stimulus presentations, even after the subject has emerged from the stressful environment. The suggestion is that such decrement is accompanied by the dynamic body temperature change as reported in the study (Fraser, 1957). In summary, the early work on vigilance in hot atmospheric temperatures appears, superficially, to support an arousal interpretation of performance results. However, a more detailed analysis indicates that reduction in efficiency is accompanied in each case by an uncontrolled, dynamic change in the deep body temperature of the observers away from both a normative and steady state.

Following these early efforts, Carlson (1961), in work on stress and performance, postulated that physiological and psychological sources of input summated on a single structure or through a common channel (see also Broadbent, 1971). One prediction from this postulate is that excessive stimulation, regardless of its origin, would result in information overload and consequently in performance degradation. To test this hypothesis, Carlson used two levels of heat, 20 °C (68 °F) and 33 °C (91.4 °F) ET, in combination with a monitoring task with three levels of display complexity. Although nine subjects participated in the experiment, only five completed the full series. The results, which are shown in Figure 2, indicated that the introduction of heat had little effect at the lower and intermediate levels of complexity but resulted in a large decrement at the highest level of display complexity.

Carlson (1961) also provided evidence of an increase in observer deep body temperature at the highest heat stress level. These data were taken as support for the initial suggestion concerning the summation of diverse stimulus inputs and also are consistent with the present position that dynamic body temperature change degrades vigilance. However, this breakdown in efficiency clearly depends on the number of stimulus sources to be observed in this work by Carlson (1961).

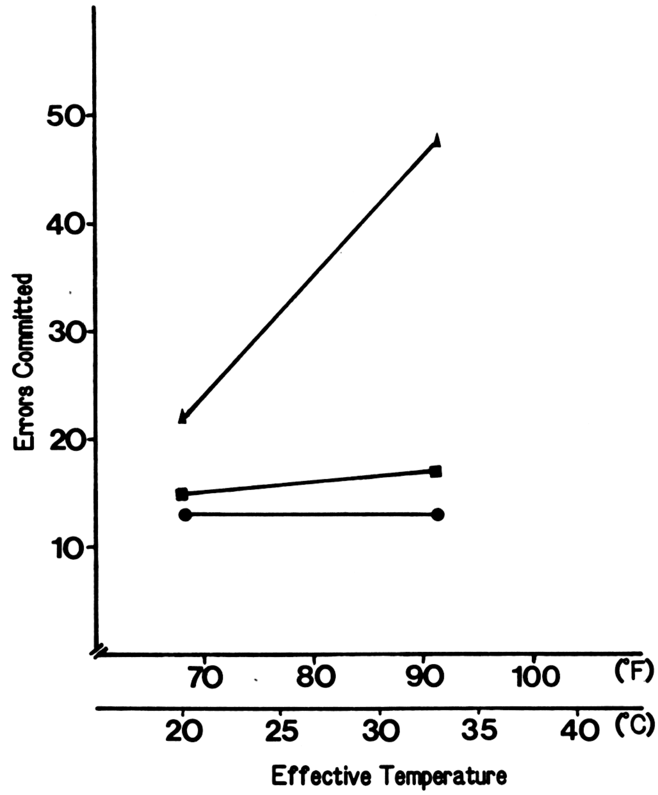

Figure 2. Vigilance errors of omission versus effective temperature for low- (●), intermediate- (■), and high-complexity (▲) monitoring displays. (Data from Carlson, 1961.)

Subsequently, Teichner proposed that the thermoregulatory mechanism acted as a general physiological arousal system, and thus detection efficiency should be related to thermal arousal through the general inverted U-shaped function. Following Teichner's proposal, Arees (1963) reasoned that performance should be high when the thermal gradient between core and skin temperatures was equivalent to that between skin and ambient air temperatures, as in normal circumstances. When the former gradient was small, that is, core and skin temperatures were close together as in heat stress conditions, detection efficiency would be poor. This would also be true of cold conditions when the gradient between core and skin temperatures is higher than that in the comfortable heat balance condition.

Arees also noted that although variation in environmental temperature was the typical way to manipulate thermal arousal, there are a number of alternate methods that achieve a similar objective. One of these is to introduce a sudden, high-intensity noise, which causes rapid peripheral vasoconstriction and consequently increases the gradient between core and skin temperatures (cf. Dean & McGlothen, 1965). Whether the manipulation of environmental temperature and noise addresses a common arousal mechanism cannot be determined directly. A recent assessment (Hancock & Pierce, 1985) has suggested that the actions of heat and noise are relatively independent, particularly in relation to their impact on performance.

Arees (1963) investigated this potential interaction by testing 24 subjects on visual monitoring of a lights matrix under three thermal conditions, 53.5 °F, 66.5 °F, and 89 °F ET. Within these temperature repetitions were embedded four groups of six subjects in which a no-alerting noise control group was compared with those hearing an early noise burst, a later noise burst, or both early and late noise bursts. For the means of the subjects tested, using only detection frequency as a dependent measure, no significant results were found for thermal condition, noise introduction, or interactions between these two factors. Initially, this appears to contradict the assertion that vigilance is degraded when the body suffers dynamic perturbation, particularly at the 89 °F ET extreme. However, Arees (1963) reported only the thermal gradient, that is, the difference between core and skin temperatures. So a direct assessment of core temperature change was not available. Also, the use of only detection frequency in the absence of data on error rate and response latency makes a simple interpretation of these results somewhat difficult. More important, the use of mean data across groups appears to have masked some systematic trends.

To examine these trends, Arees did test for a correlation by individual subject between detection efficiency and thermal strain or gradient value. He found that 10 of the 24 subjects exhibited significant linear correlations and 5 of the 24 showed significant curvilinear correlations. These 15 could be divided into three distinct groups: (a) a group of 5 whose performance increased monotonically with thermal strain; (b) a group of 5 whose performance decreased monotonically with thermal strain; and (c) a group of 5 whose functions approximated the inverted U-shaped function originally postulated. He proposed that all subjects, tentatively including those showing no correlational relation, represented phases of the inverted U-shaped function in which either the whole curve or the ascending or descending arm of the function was present. This was one of the first observations on the importance of both core and skin temperature in affecting performance, an approach that has been pursued in more contemporary work by Allan and his colleagues (e.g., Allan & Gibson, 1979; Allnutt & Allan, 1973).

There were no recorded performance or physiological effects for the brief noise bursts. Arees suggested that the brevity of effects due to the vasoconstriction, which is on the order of seconds, could not be detected in the performance of the task that required only periodic response. Indeed, it can be argued that such an effect may not be observed even in continuous tasks such as tracking (Dean & McGlothen, 1965). Overall Arees concluded some tentative support for the inverted U notion relating thermal arousal to performance. However, this interpretation is derived from the post hoc analysis of data that indicated a nonsignificant main effect for temperature condition on vigilance, and was based on the trends of only 15 of the 24 subjects tested. These observations suggest that any conclusions drawn from this work are at best tentative and should be treated with some caution.

However, although Arees' (1963) data present insufficient physiological detail to affirm the current postulate, they do not contradict the notion that it is dynamic change to deep body temperature that degrades performance. They do indicate some important variations in sensitivity across differing subjects and the eventual necessity to consider the role of both core (deep) and peripheral (skin) temperatures in influencing performance (see Allan & Gibson, 1979; Goodman, Hancock, Runnings, & Brown, 1984).

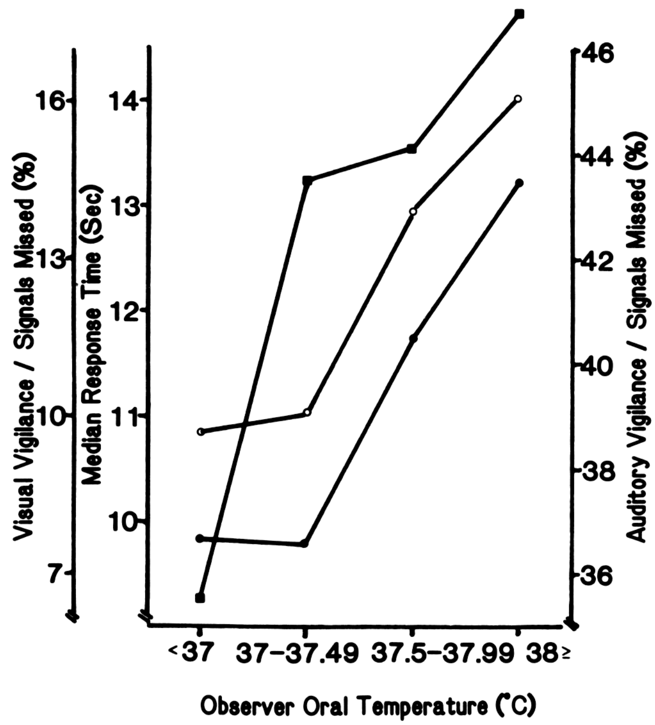

Figure 3. Latency of responses (○) and signal omission (●) for a visual vigilance task and signal omission (■) for an auditory vigilance task, as a function of performer oral temperature increase. (Data from C. R. Bell, Provins, & Hiorns, 1964.)

Following this study, two reports appeared that examined the effect of specifically increasing body temperature on sustained attention. In experiments reported by C. R. Bell, Provins, and Hiorns (1964) the exposure time depended on the level of thermal stress. As the heat level was increased across the different exposures, the time that the participants could tolerate continuous occupation decreased. Because of this variation of exposure time by condition, it is difficult to interpret results for both the visual and auditory monitoring tasks. However, vigilance efficiency plotted against performer's oral temperature, irrespective of the time and/or temperature conditions that caused the increase, exhibited certain consistent tendencies that are illustrated in Figure 3, (cf. C. R. Bell, 1964).

Grether (1973) has criticized this study because increasingly high temperatures were undertaken on successive days, which allowed both a practice effect and a potential acclimation effect to confound results. More important however, was the introduction of varying noise between 85 and 95 dB, which alone has been demonstrated to exert some performance effect on this type of sensory vigilance task (Broadbent, 1954). Despite these objections, the data indicate progressive degradation in both visual and auditory vigilance with increasing perturbation to the body temperature of the observer, as shown in Figure 3. It is interesting to note the forms that such functions take. For latency and signal omission, the function for visual sustained attention appears to

Table 1
Response Time and Signal Omission as a Function of Ambient Temperature and Change in Deep Body Temperature

Subject responses	Effective temperature (°F)		
	67	82	92
Change in deep body temperature (°F)	−0.49	−0.30	+0.53
Response time (ms)	860	800	840
Missed signals (%)	52.0	52.0	56.0

Note. Data from Colquhoun (1969).

represent a positively accelerated exponential function. However, for auditory vigilance, the dramatic increase in signal omission occurs at lower perturbations to deep body temperature. The general function as expressed in the data for visual vigilance (see also Benor and Shvartz, 1971) has been taken as support for a position relating stress to the notion of attentional resources (Hancock & Chignell, 1985), which I explore later.

Given the growing consensus of data from early studies concerning body temperature change and impairment in vigilance efficiency, a study by Colquhoun (1969) provides an important set of apparently contrasting data. He used three differing event rates and three levels of ambient temperature: 67 °F (19.4 °C), 82 °F (27.8 °C), and 92 °F (33.3 °C) ET. It should be recognized that the latter condition exceeded the 85 °F (29.4 °F) ET threshold previously noted, and the length of temporal exposure was not so brief as to curtail the increase in deep body temperature as in some other experiments (e.g., Dean & McGlothen, 1965; Poulton & Kerslake, 1965). Indeed, Colquhoun's subjects performed for 2 hr on watch, and physiological recordings indicated a slight drop in rectal temperature at the two lower conditions and a rise at the highest heat stress condition (see Table 1). Despite these physiological observations and clear main effects for both event rate and successive sessions on watch, there were no decrements due to the effect of ascending ET. Colquhoun, aware that his results were in contrast to previous investigations, postulated six potential factors to account for such a discrepancy. These were: differences in event rate, signal probability, acclimatization status, type of subject, nature of the task, and prolonged exposure time.

However, from the present synthesis, two alternative factors may be implicated. First, Hancock (in press) has indicated that a key element in performance under stress is the level of ability exhibited by the participant prior to the stress exposure. In the case of Colquhoun's subjects, considerable practice was undertaken prior to experimental sessions. This may have contributed to the relatively small performance changes found, because experienced subjects appear to be better able to resist the detrimental effects of heat compared with their unskilled peers. Second, and perhaps more important, the degree of perturbation from normal body temperature must be considered in detail as is suggested from observations in previous studies. Actual mean changes in body temperature were −0.49 °F (−0.27 °C), −0.30 °F (−0.17 °C), and +0.53 °F (0.29 °C) for the 67 °F (19.4 °C), 82 °F (27.6 °C), and 92 °F (33.3 °C) ET conditions, respectively. When mean data for overall latency and signal omission are taken from Colquhoun's work (Colquhoun, 1969, Figures 1 and 2), it can be seen that the best performance was elicited under those conditions that altered body temperature the least. Thus signal omission was 52%, 52%, and 56% and response latency 0.86s, 0.80s, and 0.85s, respectively for the three ascending conditions reproduced in Table 1. It should be recognized that these data represent group mean performance, and individual conformation to this principle requires a more detailed analysis of each individual subject's response (Arees, 1963).

The importance of the effect of time on watch was demonstrated by Mortagy (1971). In a practical investigation directed toward problems in industry, the effects of three differing lengths on watch were examined. Watches of 20, 40, or 60 min were undertaken by subjects in 74 °F (23.3 °C), 82 °F (27.8 °C), or 90 °F (32.2 °C) ET conditions. Results of this investigation are presented in Figure 4, and clearly illustrate that prolonging the period on watch has little effect at the lower room temperatures. However, when the thermal surround exceeded the threshold value at which the individual can accomplish thermal equilibration, that is, the 90 °F ET exposure, then performance decreased (cf. Mortagy & Ramsey, 1973). This observation confirms the suggestion that the value of the environmental temperature is not the key factor in dictating whether breakdown will occur.

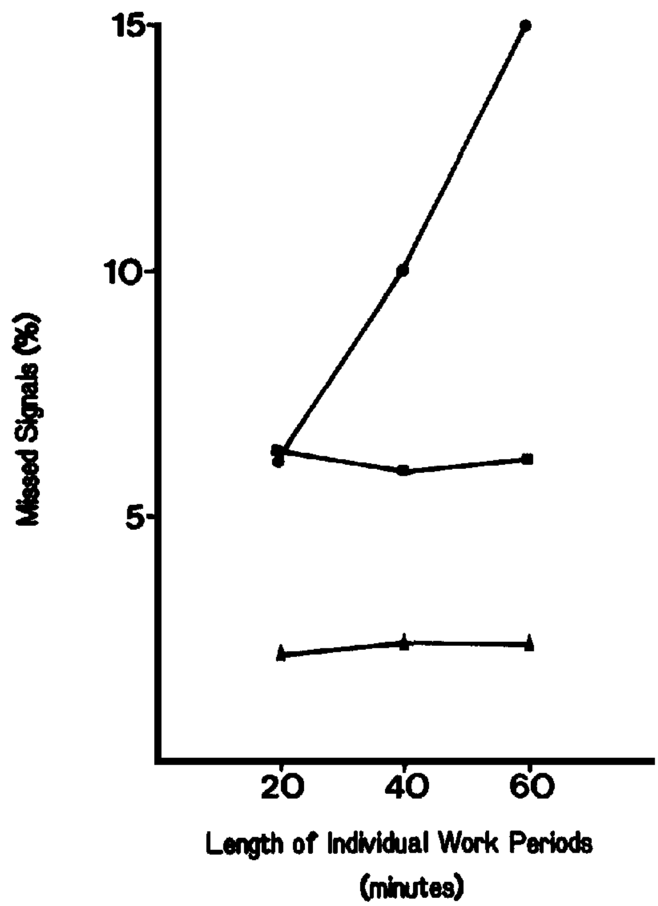

Figure 4. Signal omission versus length of period on watch at 74 °F (▲), 82 °F (■), and 90 °F (●), effective temperature. (Data from Mortagy, 1971.)

Rather, it is the combination of temperature with exposure time, sufficient to change deep body temperature, that affects performance.

Several investigations of the effect of heat stress on vigilance have been generated in response to the practical problems of work in thermally stressful conditions. Among these is an empirical analysis of augmented cooling reported by Benor and Shvartz (1971). Seven healthy subjects performed an auditory vigilance task in conditions up to 50 °C (122 °F) dry-bulb temperature while walking on a treadmill at a rate of 3.5 km/hr. In their comprehensive study, Benor and Shvartz recorded detailed physiological measures of both skin and rectal temperature. With augmented cooling these physiological parameters did not vary as environmental temperature increased, and under these conditions neither detection rate nor false reactions changed across environmental temperatures.

Without augmented cooling a different pattern of results emerged. First, the no-cooling tests were terminated if subjects' rectal temperatures exceeded 39.0 °C (102.2 °F) or if subjects reached exhaustion before the prescribed 2-hr period on watch had elapsed. Due to this restriction, the time spent in any environment varied inversely with the severity of the thermal condition. In order to compare performance across exposures, a derived value of percentage missed signals per minute on watch has been extracted from the data originally presented by Benor and Shvartz (1971). Also, because of the problems of the inertial interval, in which brief temporal exposures have relatively little effect on core body temperature (e.g., Hancock, 1984a), a combination of reported rectal and skin temperatures as recommended by Burton and Edholm (1955) has been calculated as a measure of total bodily temperature increase in this case. These synthetic data are presented in Figure 5. The general pattern is consistent for both missed signals, as shown in Figure 5, and false reactions.

These data are of particular interest as they not only affirm the present postulate that sustained attention is degraded as body temperature changes in response to the external thermal environment, but they also suggest the form such degradation takes with progressive deviation from a normal bodily thermal state (cf. C. R. Bell, Provins, & Hiorns, 1964). This function appears to take an increasing exponential form and would be consistent with a positive feedback system, which itself is the manner in which body temperature increases under the driving force of a noncompensable thermal condition. This is seen under the impact of heat disorders such as heat stroke. The potential isomorphism between breakdown in performance and physiological functioning is explored briefly in a later section, however, a fuller discussion may be found in Hancock and Chignell (1985).

As with some previous experiments, the effect of heat on vigilance has been noted as an adjunct to a fuller investigation of stressor interactions (e.g., Dean & McGlothen, 1965; Viteles & Smith, 1946). Poulton and Edwards (1974a) reported the effect of increasing heat level to 34 °C (93 °F) ET on an analogue of the Wilkinson visual vigilance test (Wilkinson, 1969a). The comparable control was a 19 °C (66 °F) ET condition. The ability to detect signals for the first versus the last 7.5-min periods of a total 30-min exposure was compared. In the heat, the signal detection metric d' decreased from approximately 2.2 to 1.9 from the first 7.5 min to the last 7.5 min, whereas the comparable decrease in the control condition was from 2.4 to 2.2. In terms of absolute decrease, d' reduced from 2.49 in the comfortable thermal condition to 2.12 in heat which represented a significant reduction (Poulton, 1977). However, the authors attributed this result not to the effects of heat, but to an uncontrolled transfer effect favoring the control condition.

In the same series of experiments on stressor interactions, Poulton and his colleagues (Poulton & Edwards, 1974b; Poulton, Edwards, & Colquhoun, 1974) examined the effect of increased temperature on the Wilkinson (1969a) auditory vigilance test. In the first experiment, Poulton and Edwards (1974b) examined the performance of 12 subjects in a comfortable 19 °C (66 °F) ET and an elevated 34 °C (93 °F) ET condition. Results indicated that in heat, subjects responded more quickly but less accurately, with a greater incidence of false detections. The latter experiment (Poulton et al., 1974) affirmed this pattern although at a slightly lower (33 °C [92 °F]) ET. The same number of subjects were tested although, because of equipment problems, results for only 10 individuals were analysed. Comparative results for these experiments are given in Table 2. When performance on each measure was broken down for sequential 7.5-min periods on watch for the latter experiment, the pattern appeared as represented in Figure 6. This illustration is constructed so that poor performance

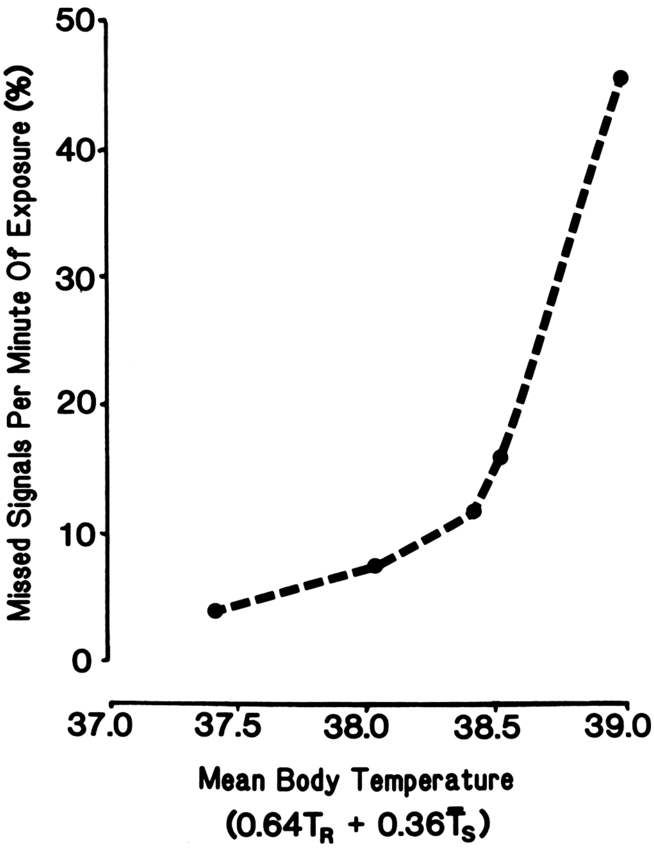

Figure 5. Percentage of missed signals per minute of exposure as a function of increase in mean body temperature. (Mean body temperature was derived from weighted values of core or rectal temperature [T_R], and skin temperature was derived from several surface sites [$\bar{T}_S$]. Data from Benor & Shvartz, 1971.)

is represented by ascending any of the three performance scales presented.

The results from the latter two experiments using auditory detection indicated a significant reduction in the percentage of signals detected. Collectively, the overall results indicated the effect of heat on vigilance was to reduce *d'*, the index of the ability to detect signals. In none of the above experiments did Poulton and his colleagues indicate the effect of heat on observer body temperature. Clearly, the 34.4 °C ET exposure exceeded the 29.4 °C ET threshold at which body temperature is disturbed. Although the vigilance task lasted only 30 min, the time spent in the heat marginally exceeded 90 min, of which the last one-third was spent in vigilance performance. In consequence it may be inferred that the subjects in these experiments experienced an increase in body temperature (although see Poulton, 1977, p. 436). This suggests that the overall change in performance with perturbation in body temperature may be one of a *d'* reduction.

Poulton (1977) also noted that there is a sizeable difference in false detections of visual compared to auditory signals. This may be due to the coarse-grained action of heat in that sweating is more likely to interfere with visual than the auditory assimilation of both signal and nonsignal stimuli. Concerning interference with vision, it is also possible that variation in visual acuity with change in core body temperature (Hohnsbein, Piekarski, & Kampmann, 1983; Hohnsbein, Piekarski, Kampmann, & Noack, 1984) is influential in the reduction of vigilance. However the impact of dynamically changing body temperature on sustained attention does not appear to be specific to any particular sensory modality. Therefore, if change in sensory acuity with body temperature is postulated as an important influence, its impact needs to be clearly demonstrated across a variety of sensory systems that may be used for vigilance.

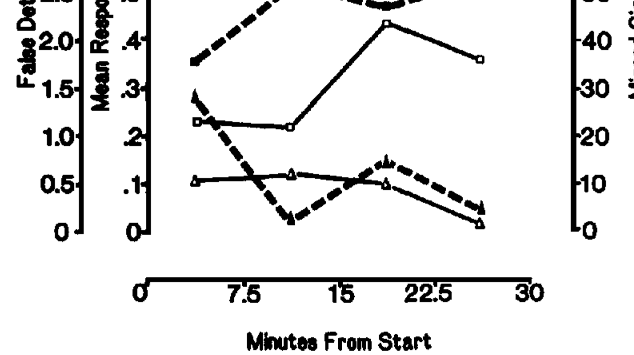

Figure 6. False detections (△, ▲), response time (○, ●), and signal omission (□, ■) for 19 °C effective temperature (ET; solid line) and 33 °C ET (broken line) conditions by sequential 7.5-min periods on watch. (Data from Poulton, Edwards, & Colquhoun, 1974.)

Table 2
Sustained Attention Performance as a Function of Environmental Effective Temperature

Effective temperature (°C)	Response time (ms)	Signal detection (%)	False detection (%)	*d'*
19[a]	640	67.8	0.43	3.28
33	610	51.3	0.68	2.63
19[b]	760	65.3	1.46	2.58
34	700	55.3	1.61	2.27

Note. The values for *d'* are near approximations taken from illustrations in the two cited articles.
[a] Data from Poulton, Edwards, & Colquhoun (1974). [b] Data from Poulton & Edwards (1974b).

In additional experimentation, Harminc (1976) examined the effect of dry-bulb temperatures ranging from 22 °C (71.6 °F) to 44 °C (111.2 °F) on a vigilance task. Significant decrement for signal omission with heat was reported. Inefficiency in vigilance capability (e.g., Harminc, 1976, Figures 2 and 3) was related to change in deep body temperature (e.g., Harminc, 1976, Figure 9) in a manner consistent with the present postulation.

The practicality of the problem of vigilance under thermal stress was elaborated by Mackie and O'Hanlon (1977) in a study of extended driver performance in heat. They indicated that driving a motor vehicle is one of the most prolonged attention-demanding tasks to which the average person is exposed (Brown, 1967). Vehicle operation under tedious conditions for extended periods of time falls under the rubric of operational vigilance. In a within-subject design, 10 men and 10 women were required to drive a 600-km route once in conditions of 67 °F (19.4 °C) on the Wet-Bulb, Globe Temperature (WBGT) heat stress scale and once in an elevated 90 °F (32.2 °C) WBGT condition.[2] All exposures took place during the day and the order of exposure was counterbalanced across subjects. Several physiological measures were recorded, including sweat rate, corticosteroid excretion, blood pressure, electroencephalogram, and electrocardiogram measures. However, oral temperature was measured only at the beginning and end of each driving segment and a general trend rather than a time-related function was consequently observed (see Figure 7). Several measures of performance and subjective reactions of the drivers were analysed. Measures of self-alertness and fatigue indicated progressive decrement with time, although some conflict appeared between what is reported in the text and the illustration for the problem of fatigue (cf. Mackie & O'Hanlon, 1977, Figure 14).

[2] The Wet-Bulb, Globe Temperature Index, first proposed by Yaglou and Minard (1957) synthesizes air temperature, relative humidity, air movement, and radiant heat. It is a superior index for assessing heat load with respect to performance capability, as noted in this article. However, typically, radiant heat is not recorded in experiments examining such performance. Consequently, the more common but less appropriate effective temperature scale has been used, particularly where such values appear in the original report.

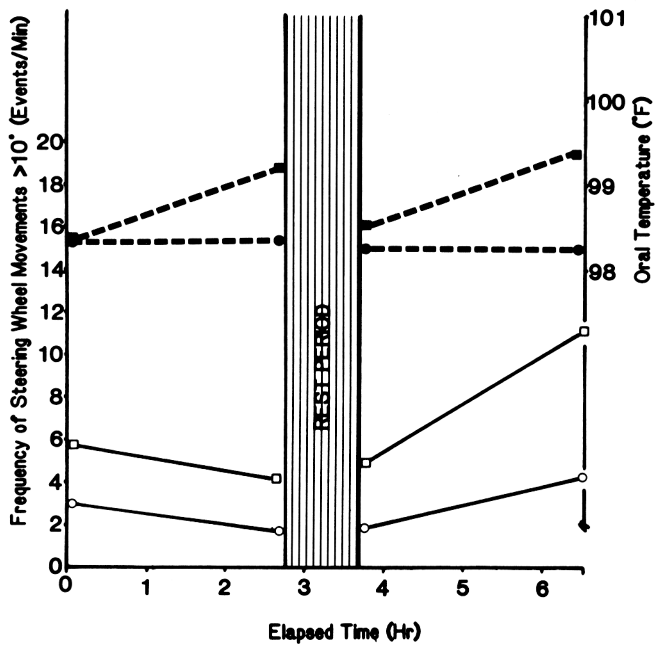

Figure 7. Frequency of steering wheel movements greater than 10° (○, □) in magnitude and increases in oral temperature (●, ■) versus elapsed time of vehicle operation. (Circles = 67° Wet Blub Globe Temperature [WBGT] Index, squares = 90° WBGT. Data from Mackie & O'Hanlon, 1977.)

In the measures of performance that were recorded, the frequency of large-scale (>10°) excursions of the steering wheel movement, reflective of recoveries after momentary lapses of attention, are somewhat analagous to the failure to detect a critical signal in a vigilance paradigm. These excursions decreased slightly with the first half of travel in both the comfortable and heat stress conditions. However, during the second half of travel, the frequency of such movements increased and this tendency was magnified by the introduction of heat. This trend is illustrated in Figure 7.

This pattern was confirmed for alternate measures of performance such as the variation in driving speed, the frequency of technical driving errors, and the rate of measurable lane drift. In summary, the authors concluded that drivers exposed to hot environments exhibited decreased precision in steering control and an increased propensity toward error during the first 150 min of exposure, compared with performance when driving in thermally comfortable conditions. These differences continued to increase with progressive temporal exposure. Consequently, these data support the current notion concerning body temperature and the sustenance of attention, but, because of limitations of the experimental protocol, these results add relatively little to the detail concerning the overall function that such a relation might possess.

Fine and Kobrick (1978) suggested that certain equivocal results that have been observed in performance under heat (see Jones, 1970, for a review) might be due to a low level of subject motivation and the relative artificiality of laboratory-generated tasks. Fine and Kobrick were also most sensitive to the potential effect of practice on the task prior to heat stress exposure (see also Hancock, in press). Consequently, they examined the capability on a military fire command task of naive individuals who undertook prior standardized practice. Motivation to perform was sustained at a high level. Subjects were exposed for 7 hr to a 33.3 °C ET condition, and in this practical investigation, the effect of altitude up to 4,300 m was also analyzed. During the 4th hr of the experiment a rest period was imposed, and in the 1st, 3rd, 5th, and 7th hr, fire commands were communicated at the rate of 30/hr. In order to simulate relatively inactive periods, Fine and Kobrick reduced the rate of communication to only 5 fire commands/hr during the 2nd and 6th hr. Performance during these hours best reflects the problem of sustained attention. Results indicated that whereas errors remained fairly constant at approximately 10% in the control condition, errors increased from 10% to 26% from the 2nd to the 6th hr in the heat.

Initially, the lack of increase in errors in heat at the 2nd hr appears somewhat in contrast to the present assertion. Although physiological data were not presented, the inference from previous indications is that body temperature would be elevated after 2 hr in a 33.3 °C ET environment. The reason for this initial lack of decrement is probably related to the sustained level of motivation of the individuals concerned. The precise effect of this important factor is deserving of more thorough empirical analysis. The failure during the 6th hr is in accord with the present proposal, although again the ability to match such decrement with change in body temperature is not directly available from the results presented in this study.

A final study in which vigilance performance has been related to body temperature change induced by heat stress has been reported by Epstein, Keren, Moisseiev, Gasko, and Yachin (1980). A sustained attention component of performance was incorporated into an overall complex psychomotor task that was performed in ETs of 21 °C (69.8 °F), 30 °C (86 °F), and 35 °C (95 °F). Participants were able to stabilize body temperature with little increase in the lower two temperature conditions. However, the 35 °C ET condition induced a dynamic and noncompensable increase in core body temperature (see Epstein et al., 1980, Figure 2). In terms of performance, subjects traded speed for accuracy in the two lowest temperatures such that the slow but accurate performance at 21 °C was contrasted with faster but less accurate performance at 30 °C ET. At the highest heat stress condition there was a general deterioration in overall performance that was both slow and inaccurate. These data provide substantive support for the assertion that performance breakdown is observed when the individual manifests a dynamic and noncompensable change in deep body temperature.

Heat: No Change in Performance With No Change in Body Temperature

Whereas the above studies attest to the notion that perturbation results in vigilance decrement, there are several reports of no performance change, and these are characterized by a lack of variation in core temperature. Among the first, Loeb and Jeantheau (1958) conducted a practical experiment on the effect of three different stressors that were imposed either singly or in combination. On a task similar to Broadbent's (1953) monitoring of 20 dials, the effects of heat, noise, and vibration stress were evaluated. It is of particular interest that Loeb and Jeantheau

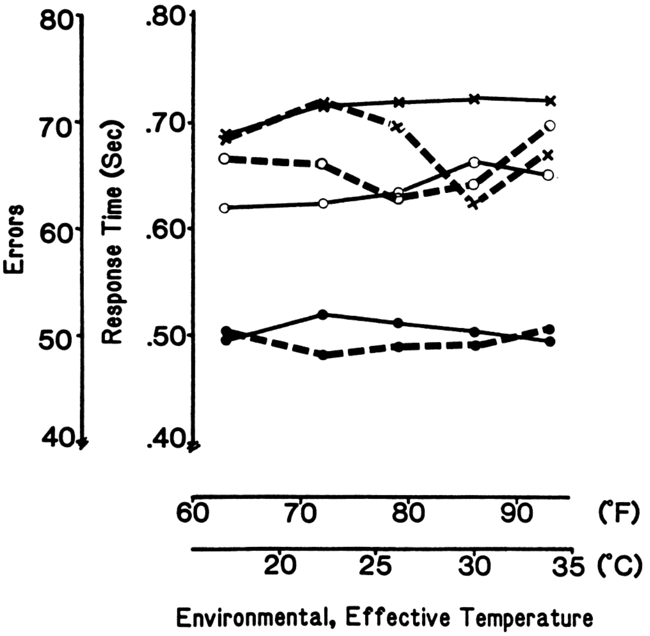

Figure 8. Environmental effective temperature versus omission error (×), commission error (O), and response time (●) in radar monitoring. (Solid line: data for the presence of 70-dB noise stressor; broken line: 110 dB noise stressor.)

noted no effect on performance with the addition of heat ranging from 110 °F (43.3 °C) to 125 °F (51.7 °C) dry-bulb temperature and 4%–24% relative humidity. It has been observed (C. R. Bell & Provins, 1962) that the comparison control condition was recorded at night, and diurnal variation in performance has already been noted as an important influence (Colquhoun, 1960). In consequence, it is possible that nighttime control performance was somewhat depressed with respect to comparative daytime performance, a factor potentially responsible for the lack of main effects. However, no variation in body temperature was recorded in association with this lack of impact on vigilance. Despite these observations. The overall study indicated the practical decrement to be expected in a multiple stress condition, although the conclusion concerning heat alone remains somewhat equivocal.

The specific effects of introducing humidity into both moderate and high-temperature environments were analyzed by Fine, Cohen, and Crist (1960). They used an auditory discrimination task in which three successive tones were presented. Subjects were required to report which of the first two tones matched the final tone, when the atypical tone represented one of four different values along any of the three factors of intensity, frequency, and duration. There were no significant effects for exposure at 93 °F (33.9 °C) ET for the 6.5-hr exposure on the auditory discrimination task. However, there are several factors that may have accounted for this lack of decrement. First, the auditory stimulus characteristics were altered by the varying environmental conditions, and hence the comparison of performance between differing temperatures was not a viable one. Rather, a discrepancy score between performance after initial exposure and just prior to exiting the environment was used. Although these data suggested comparable decrements across all four thermal conditions investigated and belied earlier observations of a Time × Thermal Condition interaction on performance (e.g., Mackworth, 1950), the study does not allow inferences concerning the absolute level of performance change. Second, the monitoring task was interpolated among other performance tasks of interest and lasted only 20 min on each of the two occasions given. Finally, monitoring was of an auditory rather than visual task, and the modality of attention is potentially an important variant with respect to absolute performance level, level of decrement, and subsequent recovery during and after exposure to an atypical thermal condition (Poulton, 1977). In sum, Fine et al. (1960) questioned the ubiquity of heat-induced vigilance decrement, but methodological inadequacies, particularly the lack of data for body temperature, clouds any interpretation that may be made.

Edholm (1963) reported a précis of a field study in which the effects of natural and artificial acclimatization were compared with performance of a nonacclimatized group. Eighteen subjects in each group experienced a 12-day desert exposure. Assessments of both physiological and performance capabilities were recorded. Among the tests was a vigilance task, although precise details of the procedure were not reported. Edholm indicated that vigilance did not vary across the three groups when control performance was compared with ability under desert conditions. As precise details of decrement were not given, a thorough assessment of the impact of heat is not directly available.

Stronger evidence for the dependency of change in performance on variation in body temperature comes from the work of Dean and McGlothen (1965). In their work on the interaction of stressors, they had occasion to observe vigilance under extremes of both heat and noise. Their data, which are reproduced in Figures 8 and 9, indicated no effect for increasing ambient temperature up to 93.0 °F (33.9 °C) ET.

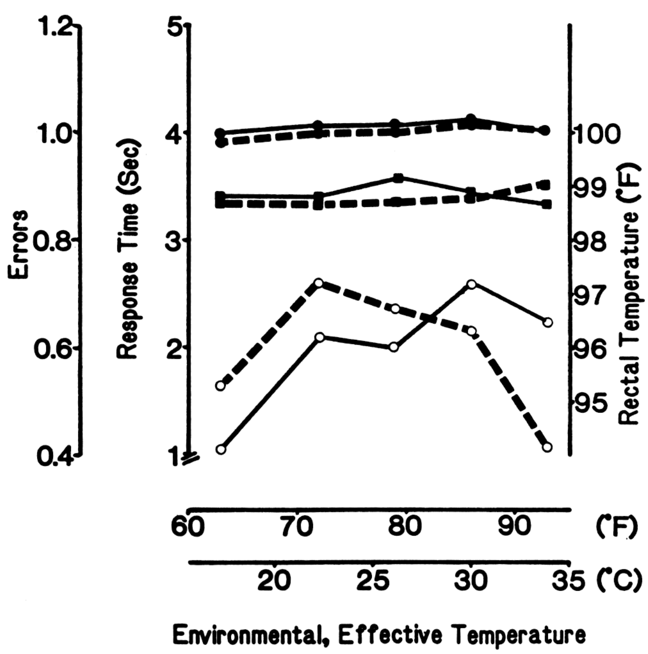

Figure 9. Environmental effective temperature versus commission error (O) and response time (●) in meter monitoring. Rectal temperature change for both tasks is also shown (■). (Solid line: data for presence of 70-dB noise stressor; broken line: 110-dB noise stressor. From Dean & McGlothen, 1965.)

Initially this result appears in direct contradiction to the previously stated observations of reduced capability in heat. This is particularly true as the highest temperature was well in excess of the 85 °F ET threshold as explored earlier. The key factor in this study was the time of exposure: a maximum of 30 min, of which only the last 20 min were used to assess performance. This length of exposure was insufficient to induce a measurable change in deep body temperature and has been described by Hancock (1984a) as an inertial interval, in which the temperature, however high, has insufficient time to perturb deep body temperature (cf. Dean & McGlothen, 1965, Figure 12) and Figure 9. This short exposure time is probably also responsible for the plethora of null results reported in the study even in the face of such stressful conditions as 110-dB noise in combination with 33.9 °C ET. Therefore these data strongly support the suggestion that it is *not* the actual ambient temperature that influences performance, but instead it is the combination of exposure time and temperature sufficient to perturb deep body temperature that degrades vigilance.

There are a variety of studies that have incorporated vigilance-type tasks into an overall performance battery to be used to assess the effects of stress. Among these, Chiles, Iampietro, and Higgins (1972) reported the effect of 34.4 °C (94.0 °F) ET on monitoring over a 75-min interval. They found no significant difference in vigilance between the heated and control environments. Although both the temperature and the exposure time were sufficient to induce a change in deep body temperature, the findings do not contradict previous observations of decrement. This is because the monitoring task was always performed in association with another task and often with more than one additional task. Also, performance periods of 15 min or less were recorded, in which relatively few signals were presented. These findings do follow their previous observations (Iampietro, Chiles, Higgins, & Gibbons, 1969; Iampietro et al., 1972), which have been incorporated by Hancock (1982) into an overall picture of performance in heat. Paradoxically, vigilance appears to be disturbed earlier and more substantially by changes in deep body temperature than is performance on multiple and complex tasks. These latter observations provide one example of this interesting phenomenon.

Heat: Static Hyperthermia Improves Performance

As can be seen from the preceding argument, the term *elevated body temperature* is somewhat of a misnomer in that it gives no indication of the individual's dynamic thermal state. Thus an absolute temperature value does not designate whether an increasing, decreasing, or static condition exists. The arguments presented above have suggested the importance of this dynamic aspect in that it can help resolve the apparently contradictory results that have included both improvement and decrement in vigilance with increased body temperature. Improved performance has only been observed when the subject has been stabilized in a static hyperthermic state. Details of these studies are presented below.

Perhaps the first to report this seemingly anomalous performance increase, Wilkinson, Fox, Goldsmith, Hampton, and Lewis (1964), exposed 12 subjects for different periods of time to an ambient condition of 43 °C (109.4 °F) dry-bulb temperature and 100% relative humidity. After the subjects had sustained increases of 0.8 °C (1.4 °F), 1.4 °C (2.5 °F), and 2.0 °C (3.6 °F) in sublingual temperature, they were removed from the heated room, and the increase was maintained by the use of an impermeable suit through which heated air was circulated at periodic intervals. Performance at each hyperthermic state was assessed for both auditory vigilance and a mental addition test.

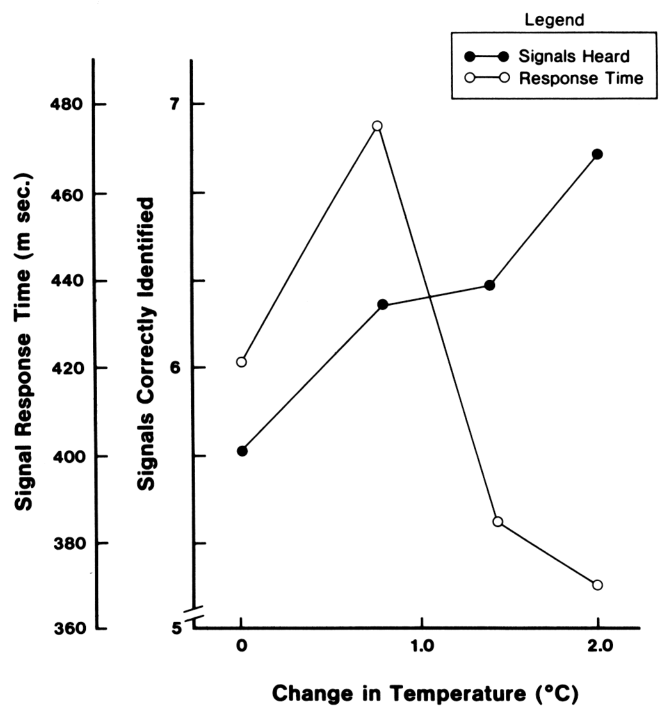

Figure 10. Response latency and signal recognition versus elevation in observer oral temperature. Zero change = 36.5 °C deep body temperature. (Data from Wilkinson, Fox, Goldsmith, Hampton, & Lewis, 1964.)

Results for auditory vigilance are reproduced in Figure 10. These data show that reaction to a 0.8 °C increase was slower but more accurate, which reflects a more conservative strategy caused by the hyperthermic level. Above this value, latency decreased while accuracy increased, indicating a true gain in performance efficiency. The key difference between this thermal manipulation and previous studies (e.g., C. R. Bell et al., 1964) is the establishment of a static hyperthermic state that lacked the stress associated with the constant body temperature increase of other experiments. Although this is an important finding, Wilkinson et al. (1964) also reported this somewhat incongruous result for mental addition, which was adversely affected by hyperthermia. This appears to cast doubt on the generality of static hyperthermia as a beneficial state.

In direct response to the anomalous findings of Wilkinson and his co-workers, and a previous failure to find any affect for temperature on vigilance (i.e., Colquhoun, 1969), Colquhoun and Goldman (1972) conducted a study on performance under controlled hyperthermia. Their subjects exercised in 103 °F (39.4 °C) dry bulb and 93 °F (33.9 °C) wet bulb. Each 10-min exercise period caused a 0.4 °F (0.2 °C) increase in deep body temperature. This gave a control condition and static elevations of 100.4 °F (38.0 °C), 100.8 °F (38.2 °C), 101.2 °F (38.4 °C), and 101.5

°F (38.6 °C) for the differing exercise periods. Using a visual vigilance task, measures of detection frequency, latency, and false responses were recorded. Unlike the facilitation reported by Wilkinson et al., no effect was found for elevation of body temperature. However, when the percentage of signals detected were divided on the basis of subjective confidence in response, results indicated some affirmation for the notion of improvement in the category of highly confident response. It should be noted, however, that in absolute terms the increase was only 5% between the two physiological extremes (Figure 11).

As a result of this increase in "certain" responses with core body temperature increase, Colquhoun and Goldman (1972) suggested that ascending body temperature influenced decision criterion. Although this is a reasonable conclusion, a number of other factors may have influenced this finding. First, Colquhoun and Goldman's subjects were highly familiar with the performance task and this is an influence on performance under heat stress (Hancock, in press). Second, a visual rather than auditory vigilance task was used (cf. Wilkinson et al., 1964) and it seems reasonable to suggest that modality of stimulus presentation may have a considerable effect on performance in that vision may be more affected by the coarse-grained actions of heat, such as sweating, than is audition. Finally, performance in Colquhoun and Goldman's study occurred in the presence of others, a factor that appears to influence performer efficiency (Warm, 1984). Although the above considerations merit some attention, the overall conclusions of Colquhoun and Goldman appear substantiated in the present assessment. They indicated that it is only when the body temperature increased that performance at a vigilance task altered noticeably in hot conditions and, further, that for highly trained subjects, such an increase must be considerable before such an alteration occurs (Hancock, in press).

The last of three studies reporting performance facilitation used only a brief 18.5-min exposure. In this study, Poulton and Kerslake (1965) asked their subjects to perform a combination of visual and auditory monitoring in parallel. As in certain previous experimental investigations, the use of repetitive exposures resulted in asymmetric performance transfer that obscured the results obtained (see Poulton, 1977). However, an overall facilitating effect for initial entry into the 30 °C (86 °F) ET environment was reported. Physiological evidence indicated raised forehead skin temperature, but measures of deep body temperature were not taken. Poulton and Kerslake speculated than by the time a significant performance change was noticed at approximately 12 min, rectal temperature would probably have *fallen*. They buttressed this argument with reference to the work of Bazett (1949). However, this is not based on direct observation and does not agree with physiological data recorded under comparable conditions (Dean & McGlothen, 1965). These data do, however, indicate some facilitation for immediate entry into a heated environment, but whether this is due to the complex nature of the performance required, the change in physiological state of the observer, or the impact of the heat per se cannot be directly determined. These data do indicate an interesting anomaly that needs further investigation, but do not contradict the postulate that static hyperthermia is beneficial for vigilance performance.

Typically, reports of improved performance under thermal stress have proven difficult to encompass for theoretical positions based on body temperature, physiological adequacy, and attention constructs. For arousal it is sufficient to equate arousal state with performance variation. However, this simple tautological view disserves some of the more substantial theoretical contributions that a thorough understanding of the notion of behavioral arousal may supply. In sum, evidence supports the contention that static hyperthermia benefits sustained attention.

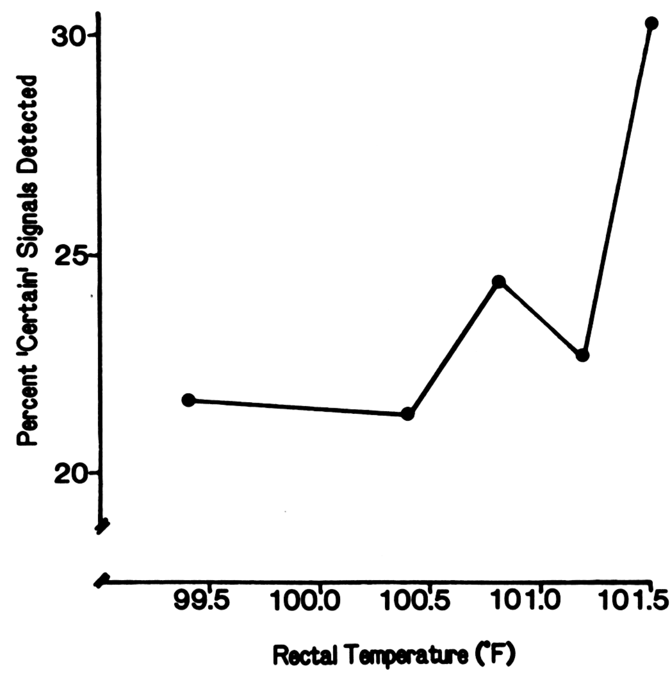

Figure 11. Percentage detection of "certain" signals versus observer rectal temperature. (Data from Colquhoun & Goldman, 1972.)

Cold: Dynamic Change in Deep Body Temperature Degrades Performance

The number of studies reporting on vigilance in reduced ambient temperatures is particularly small compared with heat stress counterparts. One of the first studies of cold was conducted by Kissen, Reifler, and Thaler (1964), whose central concern was the use of hypnosis in controlling thermoregulatory responses to reduced environmental temperature. However, embedded within this investigation was an examination of visual vigilance in 4 °C (39.2 °F) air temperature for a 1-hr period. Participants were required to distinguish randomly displayed matched pairs of a visual pattern from unmatched pairs. These patterns were presented at the background rate of approximately 1/s throughout the experiment. Results suggested that the hypnotic state reduced the physiological stress of cold. However, of more relevance to the current work are the data concerning performance, as expressed in Figure 12.

As Figure 12 shows, there is a progressive deterioration in performance with increasing exposure to cold. This is reflected in the number of correct identifications and correspondent signal omissions. It should be noted that the incidence of commission errors did not vary with exposure time. The overall performance decrement is accompanied by a progressive reduction in core temperature that follows the characteristic transient increase on immediate exposure to cold (Figure 12). These data suggest, therefore, that sustained attention decrement is related to dynamic deep body temperature change, although in the above case it is a reduction in core temperature level. This finding is consistent with information presented previously on performance under dynamic body temperature decrease as given in the reports of Mackworth (1950) and Pepler (1953, 1958).

Following the work of Kissen and his colleagues, Poulton, Hitchings, and Brooke (1965) conducted a practical evaluation of lookout efficiency in Arctic 28 °F (−2.2 °C) and a slightly more temperate 35 °F (1.7 °C) climatic conditions. There were considerable practical and methodological problems because of the action of wind and rain during one watch period. These problems were accompanied by uncontrolled performance transfer between conditions for the two groups examined. Despite these contaminants, the authors recorded a 1.2 °C (2.16 °F) fall in oral temperature during the exposure to the lower air temperature. They concluded that the reduction in performance efficiency of watchkeeping in the cold may be correlated with the dynamic decrease in body temperature. Although this is not strong evidence, it is in clear agreement with previous observations (e.g., Kissen et al., 1964; Mackworth, 1950; Pepler, 1958).

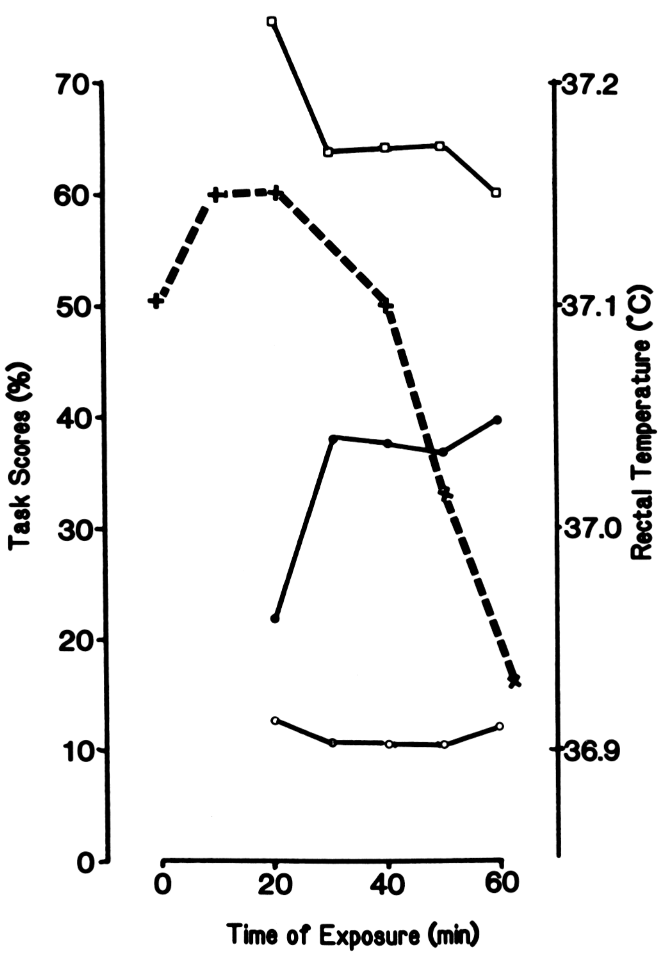

Figure 12. Errors of commission (○), errors of omission (●), correct responses (■), and change in rectal temperature (×) versus exposure time at 4 °C. (Data from Kissen, Reifler, & Thaler 1964.)

The most recent investigation of the effects of cold on vigilance was conducted by Angus, Pearce, Buguet, and Olsen (1979). They used a Wilkinson visual vigilance task and compared baseline data with that obtained during 16 days at an ambient temperature ranging from 0 °C to 5 °C (32 °F–41 °F) in Arctic conditions. The vigilance task was performed in 40-min sessions on alternate days, with one 2-day break around Day 8. Results indicated an immediate effect on signal omission. This increased by 27% from the final day of baseline measurement to the first experimental day. The authors speculated that the deprivation of rapid eye movement (REM) sleep that accompanied initial cold exposure was related to the decrement observed. Although body temperatures were measured during sleeping hours, there was no indication of their level during actual performance; therefore it is difficult to assess the role of body temperature in this case, as an indication of time-related variation in performance with thermal state was not reported. The data are interesting however, in that recovery of performance during sequential days was indicated, which may be due to a task-practice effect. This progressive recovery might also have been related to the sequential decrease in the impact of the environment on thermal state, although this remains a somewhat speculative suggestion. The authors' observations on REM sleep loss also deserve consideration. Results indicated total recovery of vigilance to baseline levels after 16 days, whereas REM recovery stood at 75% of preexposure levels. The simple correlation between measures of REM and performance was not significant. This indicated that REM loss cannot be the sole factor involved. However, using a multiple correlation technique, the authors calculated that over 90% of the variation in the vigilance performance could be accounted for by three factors: percentage of REM recovery, task days, and temperature. Decline in vigilance efficiency with dynamic perturbation to deep body temperature is suggested by the overall conclusions of the study.

Cold: No Change in Performance With No Change in Deep Body Temperature

As with the previous section, there are few studies in which the effects of reduced ambient temperature have been examined. In one exception, Teichner (1966) investigated prolonged visual detection at 55 °F (12.8 °C) and 80 °F (26.7 °C) dry-bulb temperature with a constant 40% relative humidity background. Two groups were compared that varied in their response to cold conditions as measured by cold-induced vasodilation or the so-called Lewis wave. These air temperatures were insufficient to change the deep body temperatures of either group in the experiment (see Teichner, 1966, Figure 3). Although some intergroup differences were observed in performance, means for percent detection and response speed did not vary consistently across the two temperature conditions. These results suggest using caution in simple interindividual generalizations (see also Arees, 1963). However, they support the present contention that consistent vigilance performance decrement is observed only when deep body temperature is perturbed dynamically rather than by the mere manipulation of the thermal environment per se. This study is in accord with other reports noted in the comparable section on heat, in which the elevation of the ambient temperature, which did not affect deep body temperature, failed to influence vigilance efficiency (Dean & McGlothen, 1965; Edholm, 1963; Fine et al., 1960; Loeb & Jeantheau, 1958).

Cold: Absence of Experimental Results Under Stabilized Hypothermia

There are apparently no studies in which vigilance performance has been specifically monitored while the subject was stabilized in a hypothermic state. Of the three options concerning performance variation—no change, decrement, and improvement—the least likely would seem to be no effect for such a manipulation. However, judging the likelihood of the latter two possibilities appears to be a matter of speculation. Evidence from other performance areas, such as time perception, appears to favor the notion of a slowing of response and therefore decrement (Baddeley, 1966). However, even within this latter realm, individual differences exert an important effect (e.g., C. R. Bell, 1966; Hancock, 1983). In the absence of more substantial indications, no firm assertion concerning vigilance performance under this hypothermic condition is possible at this time.

In summary, the consensus of data available concerning the thermal environment, body temperature, and capability on sustained attention tasks does not support the notions advanced by Grether (1973) and by Davies and his colleagues (e.g., Davies & Parasuraman, 1982; Davies & Tune, 1970). These authors have indicated a general decrement due to cold and facilitation in thermal conditions exceeding subjective comfort, with capability not failing until imminent physiological collapse. The present review, in contrast, indicates variation in sustained attention efficiency with a measurable change in the deep body temperature of the observer (see Colquhoun & Goldman, 1972). As indicated in the data of Benor and Shvartz (1971), this decremental function is continuous and appears to follow a positive exponential-type function. This function, typical of a positive feedback system, is mirrored in the morphology of the breakdown in body temperature itself under the driving force of some noncompensable thermal surround, such as desert conditions. Significant decrement in vigilance appears to coincide with the point at which deep body temperature change may first be observed.

This review has been restricted to those conditions in which the effect of an external thermal stress has been imposed on the individual. This does not include many studies (e.g., Bonnet & Alter, 1982; Moses, Lubin, Naitoh, & Johnson, 1978; Poock, Tuck, & Tinsley, 1969; Taub & Berger, 1976) that have examined the effect on performance of naturally occurring fluctuations in body temperature due to circadian rhythm. However, in accord with the observations on static hyperthermia, it is clear that the natural increase in deep body temperature associated with circadian rhythm is also accompanied by an increase in capability on a variety of tasks (Kleitman, 1963), including vigilance.

Discussion

There have been a number of accounts of the impact of environmental stressors on vigilance (e.g., Hancock, 1984a; Poulton, 1977) and, similarly, several proposals concerning the effect of thermal stress on a wide variety of cognitive and neuromuscular abilities (see P. A. Bell, 1981; Kobrick & Fine, 1983). These range from simple descriptive approaches to those postulating some form of underlying causal mechanism. With respect to variation in vigilance under the impact of thermal stress, there have been three basic proposals. These are physiological adequacy, behavioral arousal, and attentional-resource capacity. The utility of these three approaches is evaluated in light of the insights revealed by the preceeding differentiation of performance based on the thermophysiological state of the observer involved.

Physiological Adequacy

Perhaps the earliest notion concerning human capability in heat is that of physiological adequacy, which emanates from initial descriptive and experimental observations (Blagden, 1775a, 1775b; Ellis, 1758; Sutton, 1909). According to this proposition, measurements of body temperature, sweat rate, and other thermoregulatory actions are taken as indices of physiological state. Tolerance is set in terms of those conditions in which the thermal equilibrium of the body is first disturbed. Physiological adequacy implies that performance remains unaffected while regulatory mechanisms are effective and homeostasis prevails.

Although early experimental studies appeared to support the adequacy notion (see Connell, 1948), subsequent research failed to confirm the generality of the construct (e.g., Bartlett & Gronow, 1953; Weiner & Hutchinson, 1945). However, these early studies failed to distinguish between the type of cognitive or psychomotor performance task undertaken. With a careful differentiation between such tasks, specific increases in deep body temperature can be used to describe the limits of efficient performance in mental, psychomotor, and dual-task performance categories (Hancock, 1982). Although the concept of physiological adequacy was one of the first accounts of performance under thermal stress, its early rejection appears to have been based on insufficient recognition of the variety of tasks undertaken by the stress participants. Consequently, it has languished, disused for a considerable time. This may have been an inappropriate treatment of a useful construct.

From the foregoing evaluation of vigilance in heat and cold, where significant performance decrement is apparently induced by dynamic change in deep body temperature, the construct of physiological adequacy appears a reasonable account of the data reported. However, despite this recognition, it is important to note that it is largely a descriptive rather than explanatory account of the phenomenon at hand. Although the appeal to physiological mechanisms implies some empirical predictions, no distinct causal mechanism is identified by this proposal.

Behavioral Arousal

Perhaps the most influential theoretical account that has been proposed concerning the overall effects of stress on human performance is behavioral arousal. With respect to the effect of environmental temperature on sustained attention, this position has been presented most cogently by Poulton (Poulton, 1976, 1977). To account for the variations in performance, as outlined in the previous section, Poulton proposed five different effects founded on changes in arousal state. Initially, and after the experimental findings of Mackworth (1950) and Pepler (1958), he postulated that mild heat, sufficient to induce discomfort, facilitates performance through an increase in arousal. Such an increase is also associated with the initial entry into a heated environment (Poulton & Kerslake, 1965). Continuation in a mildly uncomfortable ambient temperature is accompanied by both the sensation of lassitude and a slow increase in body temperature, which reduces arousal and the ability to sustain attention. Poulton (1977) suggested that, should conditions be sufficient to cause a more abrupt rise in deep body temperature, then such arousing circumstances promptly improve efficiency (e.g., Colquhoun & Goldman, 1972; Wilkinson et al., 1964). As with all capabilities, the sustenance of attention fails rapidly as the individual approaches thermally intolerable conditions (e.g., Benor & Shvartz, 1971). From this post hoc perspective, the arousal construct appears to account for the diversity of experimental results reported. However, the very flexibility of the construct that allows for such encapsulation and lends supposed explanatory power is, in actuality, a liability. Thus, the arousal construct is unable to differentiate a priori which conditions will prove arousing and which depressing. Consequently, arousal remains a post hoc construction based on the various data sets reported.

In the arousal account, when performance is described solely in terms of arousal change, the argument is a simple tautology with no practical or predictive utility. However, the arousal position gains greater credence if some mediational construct is interpolated between arousal state and performance level. Such a construct was introduced by Easterbrook (1959), who postulated the restriction of cue utilization with increasing arousal level. As arousal increases from a minimal level, non-task-related stimuli are rejected, and in consequence, performance improves. With increasing arousal, task-relevant cues are filtered and performance is diminished. This form of construct results in the classic inverted U-shaped function matching arousal with efficiency. One important element of this account, not commonly recognized, is that the correct rejection of non-task-related cues, which gives rise to the ascending arm of the inverted U, must be a somewhat different process from the subsequent elimination of task-relevant cues. This is because the former requires some form of selection, whereas the latter process is some general form of degradation. Consequently, a further construct is essentially needed to account for the two different processes illustrated. In previous work (Hancock & Dirkin, 1983; Hockey, 1970), it has been suggested that attention may be able to account for such actions. This proposal is explored in more detail in the next section specifically devoted to attention.

In sum, although arousal has been a useful construct in accounting for performance variation under stress, and has a substantive physiological basis, its ubiquitous application has been questioned (Broadbent, 1963). Also, its composition as a unitary entity has been recently criticized (Hancock, 1984b). For a more detailed examination of the current status of the arousal notion, see Hockey and Hamilton (1983). In conclusion, the simple arousal construct is failing as a descriptive account, whereas its use as a causal explanation has always been somewhat suspect in that on most occasions the appeal has been to some vague physiological mechanism that often remains undefined.

An interesting exception to the above statement is the recent work of Sanders in which he attempts to relate stress and arousal to a linear-stage model of human information processing (Sanders, 1983). Briefly, he outlines a model that relates three energetic supply systems, as envisaged by Pribram and McGuiness (1975), to specific cognitive processing mechanisms. Arousal, effort, and activation are linked to processing stages of stimulus preprocessing, feature extraction, response choice, and motor adjustment. It is suggested that stress arises when the effort mechanism is overloaded over a period of time, or fails completely in adjusting necessary energetic requirements. This model provides some interesting insights into the mechanism of stress and is superior to the simple arousal constructs that precede it.

Attentional Resource Capacity

In contrast to a linear-stage model of information processing, the human may be characterized as possessing a limited pool of attentional resources (Knowles, 1963). These resources may be distributed among tasks, or elements of tasks, in order to accomplish successful performance. Kahneman (1973) viewed these resources as residing in a single global pool to be allocated as appropriate to demand. As resources themselves have a finite limit, so the human has limitations on both single- and multiple-task abilities. Wickens (1980) has elaborated on this position, to include structure-specific resource pools, thus integrating a resource model with the linear-stage approach. Specific research pools are differentiated by modality of stimulus assimilation, decision making, and mode of response. Considerable support for this position is gained from observations of *difficulty insensitivity,* which are occasions on which two tasks may be performed simultaneously, or time-shared, with no appreciable reduction in the performance efficiency of either task. There have been some recent objections to the methodology used in experiments that support the multiple-resource model (Damos & Lyall, 1984), and a general critique of the notion of attentional resources by Navon (1984), who was instrumental in introducing the idea of attentional resources originally. However, the full elaboration of these arguments is beyond the scope of the present work. (For more complete discussions, see Wickens, 1984, and Parasuraman & Davies, 1984). Rather, my central concern in this article is with the impact of stress on attentional resources, and particularly with how stress might influence the performance of a task requiring the long-term sustenance of attention.

The foregoing arguments suggest that stress acts to drain attentional resources. Further, from evidence on vigilance it appears that stress sufficient to perturb efficient homeostasis, that is, to cause an uncontrolled rise or fall in deep body temperature, results in significant performance decrement. This position is somewhat reminiscent of that adopted by Cohen (1978, 1980), who reasoned that the threatening nature of stressors demand attentional resource capacity and that prolonged demand results in shrinkage or cognitive fatigue. However, Cohen suggested that stress both competes for and drains resources, without specifying the level of stress at which such a draining process becomes critical. In the present work, such a critical point is identified as 85 °F ET for heat stress, where an uncontrolled rise in deep body temperature may be observed.

For vigilance, the notion of physiological adequacy is particularly descriptive of the summary of data reported. However, it does not describe the increases in performance capability, and, further, it requires the mediational attentional construct to provide some element of causality. The use of attention is also particularly appealing for two separate reasons. First, it has been indicated that those tasks that demand greater attention for their successful completion are most vulnerable to the effects of perturbation to deep body temperature (Hancock, 1982). Vigilance, as reviewed in this work, is particularly vulnerable, such that any perturbation to deep body temperature is enough to affect efficiency (see also Hancock & Pierce, 1984). A second reason is that if stress acts to drain attention, then those individuals who through some strategy need to devote less attention to successfully perform the task should prove less vulnerable to stress effects. Hancock (in press) has indicated that individuals who are skilled on the task they are performing, and are able presumably to use relatively attention-free automatic-type processes, clearly suffer less adverse stress effects than their unskilled peers (see also Schneider & Shiffrin, 1977).

The linkage of stressor effects and the resultant diminution in attentional resource capacity suggests the use of psychological measures (cognitive performance) as predictive of imminent physiological breakdown under extreme thermal stress. Hancock and Chignell (1985) proposed that, outside of a comfort zone, there are regions of adaptability to stressors, with the zone of psychological adaptability being enclosed within the zone of physiological adaptability (Hancock & Chignell, 1985, Figure 1). In this view, breakdown of performance on psychological measures would be directly reflected in change of physiological state. Thus performance on attention-demanding cognitive tasks may be used as a form of early warning signal for the loss of regulatory homeostasis or physiological adaptability. The connection between thermal stress and attentional resource capacity is a natural one given that the level of thermal stress induces instability in core temperature. Cognitive processes are liable to be susceptible to fluctuations in core temperature and associated change in central nervous system temperature (Goodman et al., 1984; Hancock, 1983). This rationale has been used to justify deep auditory canal temperature as a reflection of mental workload (Hancock, Meshkati, & Robertson, 1985).

The notion of narrowing, as seen in the work of Easterbrook on cue utilization, is also important in understanding the effects of stress on attention. Clearly, if stress acts to drain attentional resources, then less resources are available to perform any particular task. Under such conditions, the optimal performance strategy is to use what resources are left available to process task-relevant cues. This appears to be the tactic adopted by the perceiver, but with the caveat that cues that are processed are those of *perceived* highest salience, which may or may not coincide with those of greatest task relevance (Cornsweet, 1969; Easterbrook, 1959). This concept has been explored most thoroughly in experiments by Hockey using noise as a stressor (e.g., Hockey, 1970). Recently, we have demonstrated that the narrowing effect is an attentional rather than a visual process. This was accomplished by showing superior response to task-relevant and perceived salient cues in the visual periphery, compared with less relevant but more centrally placed comparison signals (Dirkin & Hancock, 1984). There are a variety of empirical studies that demonstrate the narrowing phenomenon. Among those using heat stress, those by Bursill (1958) and Provins and Bell (1970) are most notable. Results from their work using dual-task performance imply that stress drains rather than competes for attentional resources. However, a clear and unequivocal demonstration of this phemomenon under the impact of both extremes of heat and cold awaits a more thorough experimental investigation.

In the review sections concerning dynamic change to deep body temperature and its functional relation with performance efficiency, it was noted that above the threshold at which deep body temperature was perturbed, performance was degraded, and this function took the form of an increasing exponential. It was also recognized that this same function describes physiological breakdown under the driving force of an extreme thermal condition. In other work (Hancock & Chignell, 1985) we have attempted to explore the implications of this potential isomorphism and the possibility that is may represent some more ubiquitous stress effect.

In summary, stress drains attention. With less attention the perceiver is constrained to adopt a tactic of narrowing onto cues of perceived task salience in order to sustain successful performance for as long as is feasible. Individuals who are skilled on a task have the opportunity to use relatively attention-free automatic processes that leave them less vulnerable to the impact of the stressor. Parenthetically, those individuals who have familiarity with the stressor and are acclimatized to the stressful conditions also suffer less (Wilkinson, 1969b). However, this may represent amelioration of the physiological impact of the stress rather than the influence of attentional capacity per se. Finally, unsupportable conditions drain all attention resources and this leads to the termination of purposive behavioral activity, or unconsciousness. The continued impact of the stress eventually supersedes physiological capability and this represents the termination of life-sustaining functions, or death.

After exploring the detrimental effects of temperature, it is important to redress the balance somewhat by indicating those occasions on which hyperthermia improves performance. This occurs when the individual is established in a static hyperthermic state (Colquhoun & Goldman, 1972; Wilkinson et al., 1964). These conditions are similar to those observed during the sequential increase in temperature associated with the circadian rhythm. Under these circumstances, in which the relative rate of change of body temperature is small, performance also improves with ascending temperature level. These indications suggest that both absolute level and rate of change of deep body temperature mediates the impact on attention.

In conclusion, it should be noted that not only the level and rate of change affect performance, but also the concomitant change in peripheral or skin temperature. Although core temperature has been implicated in the speed of performance (Allnutt & Allan, 1973; Hancock, 1983; Hoagland, 1933), the rate of error has been associated with fluctuation in skin temperature (Allan & Gibson, 1979). With respect to vigilance, the relation between these two measures and performance largely remains to be explored. A fuller picture based on these more comprehensive physiological measures awaits further experimentation.

Summary

In this article I have proposed that the key factor in determining change in vigilance under thermal stress is the thermophysiological state of the observer involved. When conditions are insufficient to change deep body temperature, performance remains essentially unaffected. However, thermal stress exposures that perturb deep body temperature away from both normal and steady-state conditions impair vigilance, while static hyperthermic states are

beneficial with respect to sustained attention. The insights derived from sustained attention performance under thermal stress are potentially useful for the construction of an overall theory of stress and attention. Whereas initial efforts have confirmed such utility (see Hancock & Chignell, 1985), the elaboration into a full theoretical perspective demands long-term efforts and an integration of understanding of the action of a variety of stressors on human behavior that has yet to be achieved.

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