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Task Categorization and the Limits of Human Performance in Extreme Heat

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This paper examines human performance limitations in differing task categories in conditions of elevated ambient temperature. Analysis of extant data affirms that decrement in the three task categories, namely: 1.) mental and cognitive skills; 2.) tracking and 3.) dual task performance, may be expected as environmental exposure exceeds 85°F, effective temperature (E.T.). Further, the systematic changes in impairment onset with tasks requiring differing levels of response complexity in varying time, E.T. conditions, are documented. These changes imply earlier heat stress related decrement in those task categories which require greater response complexity. The proposed thresholds of performance impairment are subsequently equated with absolute, physiologically noncompensable, rises in deep body temperature. Support for the notion that prescribed rises in deep body temperature may delimit efficient performance in each category is found in studies which have examined task performance in situations where deep body temperature has been independently manipulated. Performer skill level is posited as potentially most influential in the mitigation of such heat induced decrement.

FOR OVER THREE DECADES psychologists have reported contradictory findings concerning human performance in elevated ambient temperature. While some investigators have emphasized an initial stimulating effect on perceptual efficiency with immediate exposure to extreme heat (34) others have indicated performance decrement under relatively mild thermal manipulations (43). Jones (23) has attributed the failure to produce a coherent account of performance under thermal stress, in part, to a lack of methodological consistency, particularly in the specification of the time and intensity of heat conditions across varying experimental procedures. However, some of the apparent conflict may be resolved by analysis of imposed task structure. For the most part, previous reviews of heat stress and performance have failed to differentiate on this basis.

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One exception is the report by Grether (18) in which five task categories were outlined. These were: 1.) time estimation; 2.) reaction time; 3.) vigilance and monitoring; 4.) tracking; and 5.) cognitive and other skills. In the first two categories, increase in speed of observation was directly related to environmental and body temperature increase. Vigilance performance was optimal at approximately 80°F on the (E.T.) effective temperature scale (20,21). All other skills exhibited a tendency toward decrement as environmental temperature exceeded 85°F E.T. This latter temperature, as Grether notes, is the point at which complete bodily physiological compensation ceases and the performer experiences an uncontrollable increase in deep, or core, body temperature (25).

The current synthesis focuses on the effects of extreme thermal stress on performance in three task categories: 1.) mental and cognitive skills; 2.) tracking; and 3.) complex or dual task performance. These tasks have in common the requirement of continuous subject participation. In each of the categories, time spent in task response exceeds that of subject quiescence. Such activities are in direct contrast to tasks requiring intermittent response but continuous participation, e.g., vigilance, where the subject experiences periods of quiescence which exceed the time spent in active response. These latter tasks and their susceptibility variation under extremes of thermal conditions have been previously reviewed elsewhere (18,27,33).

Using a time/temperature intensity framework, results from the three task categories are compared with human physiological tolerance to high ambient temperature conditions. The overall synthesis employs a mathematical function, outlined by Houghten and Yagloglou (20), to equate behavioral performance limitations and physiological tolerance to absolute rises in deep body temperature. Results are compared with studies which have examined performance in paradigms where deep body temperature has been manipulated independent of environmental conditions. The consistent observation emerges that where task category is specified, certain prescribed rises in deep body temperature connote the limitation of completely efficient task performance.

MENTAL AND COGNITIVE SKILLS

It was Wing (42), from an analysis of 14 studies reporting time-related task decrement in elevated ambient temperature, who suggested that the time/temperature intensity curve for unimpaired mental performance lies well below the comparable thermophysiological tolerance curve at every point in time. This limit was utilized as the National Standard for temperature tolerance during sedentary work performance (28).

Recently, the paucity of empirical support for the above interpretation was indicated, and in a revision of tolerance limits Hancock (19) suggested marginal decrement in mental ability before imminent heat collapse. The latter assessment was derived from the work of Blockley and Lyman (5) on numerical comparison and addition in extreme heat conditions and the reports of Ramsey, Dayal, and Ghahramani (36) on mental multiplication, Chiles (10) who employed a complex symbol matching task and Mackworth (26) who utilized both a telegraphic reception and mental arithmetic assessment. Although the impairment of mental performance was attributed to the gross effects of imminent heat collapse, it was apparent that physical control situations which required constituents of motoric performance might prove more susceptible to thermal stress impairment.

The tolerance for unimpaired mental performance was posited as vulnerable to those factors which affected the thermophysiological limit. Repeated exposure and subject motivation were posited as factors which acted to elevate the absolute limit while concomitant physical exercise was suggested as influential in the depression of the absolute values. In addition, mental performance impairment was thought to be mitigated by specific task skill. Increasing task response complexity was also suggested as a factor which might induce earlier stress related decrement (19). A summary of these findings, presented for a 120 min. period may be found in Fig. 1. The illustration suggests that not only does the limit for unimpaired mental performance lie in close proximity to that of physiological tolerance but also that curves of similar morphology may be fitted through the points derived from studies in the mental task category and that for heat tolerance. These curves represent rises in operator core temperature of 3.0°F for heat tolerance and 2.4°F unimpaired mental performance.

TRACKING

Perhaps the most widely studied physical control action in thermally stressful environments is that of target tracking. In a recent assessment, Dixon, Copeland, and Halcomb (11) indicated that three factors involved in tracking and pursuit tasks (i.e., fine control sensitivity, arm-hand steadiness, and movement analysis) may be tentatively shown to exhibit performance decrement at about 87°F, E.T. (37,39,40). However, a consistent finding with weighted handle or heavy pursuitmeter per-

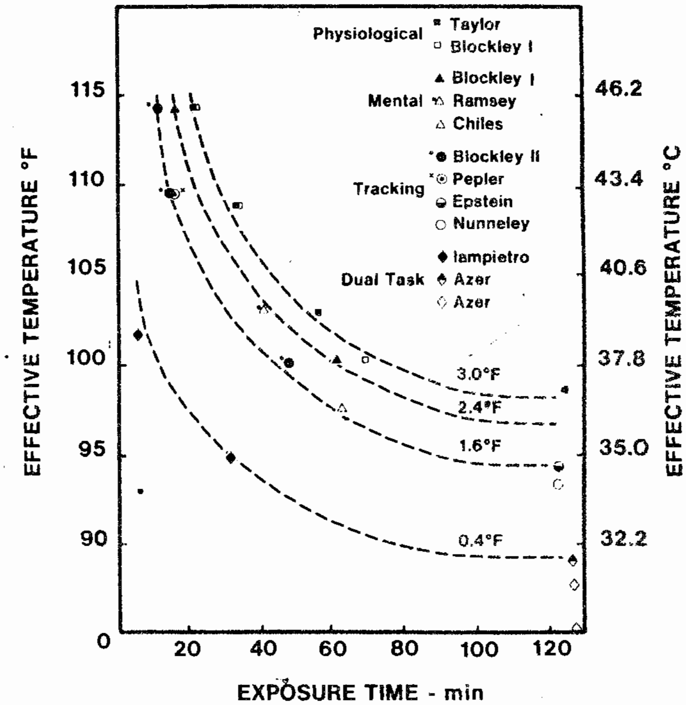

Fig. 1. Results from studies reporting decrement (filled symbols) and no decrement (unfilled symbols) in three behavioral task categories and for physiological heat tolerance. Triangular symbols represent mental and cognitive performance, circular symbols represent tracking performance, diamond symbols signify dual-task performance and square symbols represent physiological tolerance. Superimposed are dashed lines representative of prescribed rises in deep body temperature which accrue from time, E.T. intensity specifications outlined. These absolute values for the rise of body temperature are given on each curve. Names are of the first author for each study.

formance in elevated ambient temperature is the reduction of performance efficiency in conditions above only 80°F, E.T. (9,31). Consequently, Dixon et al. (11) advocated some degree of methodological consistency concerning the relationship between body temperature and time and condition of exposure, to fully assess tracking performance in high temperatures. The current section seeks to examine tracking results within such a framework.

The most comprehensive study of human performance in extreme thermal transients was by Blockley and Lyman (5,6). In the latter work, four aircraft pilots were required to reproduce an experimental flight pattern in thermal conditions of 100.5°, 109°, and 114°F, E.T. Performance on repeated 4-min trials was compared with that produced in an 80°F, Dry Bulb, thermally comfortable environment. The results suggested that the onset of performance decrement was directly related to individual tolerance time and furthermore, heat stress induced deterioration was in part mitigated by superior operator skill level. The mean time for decrement onset in this study was 51.75 min for the 61-min exposure at 100.5°F, E.T., 21.25 min for the 29-min exposure at 109°F, E.T. and 12.5 min for the 21-min exposure at 114°F, E.T.

In a subsequent replication, Pepler (32) utilized one of the temperatures—109°F, E.T.—but was forced to construct an equivalent E.T. condition using a lower air temperature value with a higher relative humidity. Subjects were required to keep a pointer aligned with a target mark which moved across a 4-in aperture with a mean frequency of 0.5 c.p.s. The findings were consistent with the conclusions of Blockley and Lyman as performance deterioration began during the last 10 min of the exposure, after 20 min of the 30-min tolerance at 109°F, E.T. This Pepler noted as an increase of 0.9°C (1.6°F) in core body temperature over a resting level.

Several studies (37,39,40) have monitored tracking performance throughout ascending ambient temperature. In reviewing the work of Viteles and Smith (40) it has been argued that the effect of compound stressors, as evinced by the experimental investigation of heat and noise in that study, is inappropriate for the determination of performance limits in heat alone (19). However, their general conclusion of tracking performance deterioration at 87°F, E.T. is in accord with the conclusion proposed by Grether (18).

Teichner and Wehrkamp (39) concluded from their results that performance efficiency on a pursuit rotor task degenerated either side of an ambient 70°F condition. Unfortunately, their temperature specifications were expressed in Dry Bulb values only, which precludes assessment based directly on the E.T. Scale. This absence of precise heat load specification may account for their data which imply greater tracking performance decrement with a decrease of 15°F away from 70°F, optimum, compared with an equivalent 15°F increase. Without more complete information concerning imposed thermal load, results from this study are difficult to synthesize into an overall picture of thermal stress and tracking performance.

Russell (37) used a wide range of ambient temperatures (−10°C to 40°C; 14°F to 104°F) to determine the effect of heat on movement and pressure tracking. Although movement tracking exhibited signs of impairment at each extreme of the ambient temperature range employed, pressure tracking showed no effect for extreme heat. Russell's subjects were exposed up to 29.44°C (84.99°F) on the Corrected Effective Temperature Scale, for a period of 73 min per cycle of experimental observations; he reported that within the limits of the Effective Temperature range used, there was no systematic effect for repeated exposures on either movement or pressure tracking. He concluded that performance impairment appears when ambient temperature varies outside rather narrow limits. However, this impairment was dependent upon individual task characteristics.

The work of Mackworth (26) has been used previously to support the contention that tracking performance is seriously degraded by relatively mild heat stress conditions. However, the primary aim of his experiments was to investigate the effect of a hot, moist atmosphere on task performance requiring prolonged but intermittent heavy physical effort and precise muscular control. The concomitant physical exercise in pursuit tracking, when handle weight varies up to 50 lb (22.7Kg), combines with the profile for increasing core temperature due to environmental heat stress alone. In addition, Mackworth measured body temperature at the termination of tests rather than during actual performance. Therefore, from this work, it is difficult to relate precisely the time onset for performance decrement to absolute deep body temperature increase.

In a recent report, Nunneley, Dowd, Myhre, Stribley and McNee (30) examined the effect of two heat stress levels on three configurations of plant difficulty within a compensatory tracking task. Highly trained subjects were exposed for 120 min to conditions of 31.8°C (89.2°F) and 34.4°C (93.9°F), E.T. When compared to performance in a thermally comfortable environment, results indicated no effect for heat on the two more difficult plant functions. The simplest task produced a small but significant improvement in performance in elevated temperatures. Both arousal and neurological accounts of performance under thermal stress were discussed but neither position was directly supported by the data from this study.

A similar exposure time was used by Epstein, Keren, Moisseiev, Gasko and Yachin (12) to examine complex psychomotor task performance in 30°C (88.2°F) and 35°C (95°F), E.T. When compared to a comfortable 21°C (70°F), E.T. condition, even highly motivated subjects were unable to maintain performance efficiency in the heat. Thermally induced impairment in the complex task, which included elements of vigilance, tracking and performance speed, was partly dependent on the level of complexity set. Epstein *et al.* suggested that psychomotor performance deteriorates before physiological parameters are impaired. However, their results, which include a speed accuracy trade-off, imply greatest performance decrement at the highest temperature exposure, 35°C (95°F), E.T.

The results from these major studies, concerning human tracking performance in extreme heat stress, have been plotted as points representative of significant decrement or no decrement, in an exposure time, E.T. framework. These are illustrated by the circular symbols in Fig. 1. Decrement is most often calculated as a significant deterioration from the level of performance of the same task in a thermally comfortable environment. A perusal of these findings suggests that some degree of consistency is observed, across differing studies, with regard to the actual limit of performance impairment onset, irrespective of the length of exposure time. This limit for completely efficient tracking performance lies below the comparable tolerance for marginally impaired mental performance (triangular symbols) and below that illustrated for thermophysiological tolerance (square symbols) which are also presented in Fig. 1. The limit shown for tracking performance, expressed as a dashed line, represents a rise of 1.6°F in deep or core body temperature. This increase accrues from all exposure time, E.T. combinations that the line describes. The single figure value is in direct agreement with the observation of performance decrement in tracking efficiency at a rise of 1.6°F deep body temperature, which was found experimentally by Pepler (32) and is consonant with the tracking performance limitations expressed by the other major studies reviewed. The comparison across task categories and the precise derivation of deep body temperature elevation in the time, E.T. framework will be discussed in the final, synthesis section of the paper.

DUAL TASK PERFORMANCE

There have been a limited number of investigations concerning complex or dual task performance in high ambient temperature conditions. Bursill (8) implicated attentional narrowing under heat stress, up to 95°F, E.T., to account for performance decrement on a concurrent peripheral visual reaction time (RT) task. Subsequently, Provins and Bell (35) reported an initial beneficial effect for a similar temperature but in contrast to Bursill found no long term performance breakdown. This discrepancy between the two studies may be attributed to differential difficulty of the employed central task. While Bursill used a centrally located pursuitmeter which imposed considerable attentional demand, Provins and Bell utilized a Serial Reaction Time (SRT) configuration of lesser difficulty. The latter report provided some evidence of physiological changes but these were based only on initial and final mean oral temperature which is most probably insufficient as a representative measure of deep body temperature value. Neither of these studies gives information concerning time-related performance variation or concomitant time profiles for increase in deep body temperature. Consequently these results are not integrated into the time-temperature intensity framework of performance limitation given in Fig. 1.

In contrast, Iampietro, Chiles, Higgins and Gibbons (22) specifically related the time limit for unimpaired dual task performance in two heat stress conditions. Time sharing ability on paired combinations of arithmetic, monitoring and tracking tasks was unimpaired after 30 min at 95°F, E.T. At the more severe exposure, 101°F, E.T. performance decrement was manifest sometime after 5 min. Iampietro *et al.* indicated that such time-shared performance denies the subject the opportunity to muster "reserves," presumably of attention, which are available in single task performance. This denial of attentional focusing may be instrumental in accounting for earlier time related decrement onset in dual-task paradigms.

The final limit for dual-task performance is derived from the work of Azer, McNall and Leung (4). For the 120-min exposure they noted significant deterioration in both central tracking and peripheral reaction only in a 90°F, E.T. condition. This reliable decrement was not observed for corresponding exposures at 88° and 85°F, E.T. However, it is interesting to note that the highest E.T. condition was constructed with the highest relative humidity rating and is possibly indicative of the differing contributions of air temperature, air velocity and relative humidity to performance decrement at any one E.T. level.

In common with results from those studies examining tracking performance, the limited points adduced from work reporting dual-task performance decrement have been illustrated as the lowest dashed line in Fig. 1. This represents a deep body temperature limit of 0.4°F rise in core temperature to connote the onset of inefficiency in situations requiring concurrent task performance.

SYNTHESIS

In addition to the points plotted for each of the three behavioral task categories outlined, Fig. 1 contains a limit for the human physiological tolerance to extremes of elevated ambient temperature. There have been several methods of assessing such tolerance. Two of these methods, time-temperature intensity specifications (5,6,38) and a limit prescribed by an absolute rise in body temperature (25) are illustrated in Fig. 1. Alternately, Blockley, McCutchan, Lyman and Taylor (7) assessed tolerance by a maximal rate of heat storage per unit body area while Kaufman (24) used a synthesis of several of these methods. In a comprehensive review Gorodinskii and his colleagues (17) indicated that a rise of 3.0°F (1.6°C) in deep body temperature effectively represented the thermal tolerance limit for the human operator. This limit, although possibly susceptible to factors such as repeated exposure, has been included as the uppermost dashed line in Fig. 1.

In order to produce any curve representative of a single value for a rise in deep body temperature within the time, E.T. framework shown, it is necessary to examine the observations of Houghten and Yagloglou (20) who first elucidated the E.T. scale. In their original formulation they produced a function which related the rate of increase in core temperature per hour, to the E.T. of the ambient thermal environment. For example, conditions of 95°F, E.T. caused an increase of 1°F in deep body temperature, per hour of exposure, Fig. 2. Later experimental work by Lind (25), utilized in argument by Grether (18), confirms one implication of this function, namely that complete thermophysiological compensation to environmental conditions continues up to a value of 85°F, E.T. As temperature increases above this level core temperature of the exposed subject begins to rise at a rate dependent on extant conditions.

The thermophysiological limit which was derived from time, E.T., specifications (5,6,38) was transformed, through the use of this function and the 3.0°F limit which results, represents a direct agreement to the mean absolute value for core temperature limits derived from a review of many studies (17). Similarly the time, E.T., specifications for each of the three task categories outlined were transformed through the use of the same function and each point may be compared with the line representing prescribed rises of 2.4°F deep body temperature for marginally impaired mental performance, 1.6°F rise in deep body temperature for degraded tracking performance and finally, 0.4°F for the limitation to successful dual-task performance. As with the limit for thermophysiological tolerance, these thresholds, adduced from time, E.T. combinations, may be directly compared

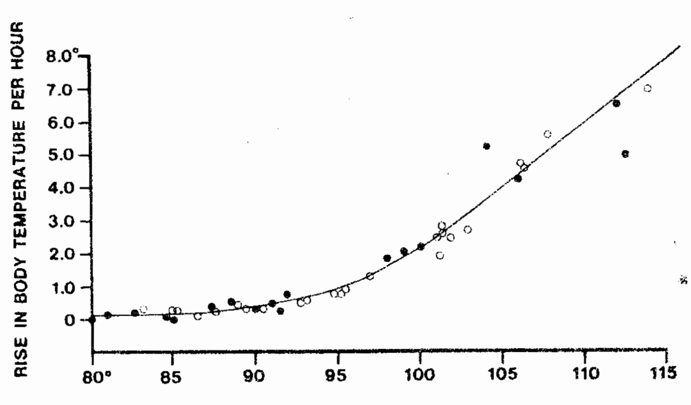

Fig. 2. Rise of body temperature in °F per hour against the Effective Temperature (E.T.) of the environment. Redrawn, after Houghten and Yagloglou (20) with publisher's permission.

to studies of mental and tracking performance where deep body temperature has been manipulated independently of ambient thermal environmental conditions.

Wilkinson and his colleagues (13,44) manipulated deep body temperature increase to steady state conditions of three different levels, namely 37.3° (99.14°F), 37.9° (100.22°F) and 38.5°C (101.3°F). The first value, was noted as a rise of 0.8°C over the normal resting value which was reported as 36.5°C (97.7°F). When body temperature was elevated to the highest value both speed and accuracy in the mental task, mathematical addition, were impaired. this was with reference to the normal deep body temperature value, which produced inferior performance when compared to that at 37.3°C (99.14°F) (*cf.* 41: Fig. 4c, 4d). They concluded that mental performance decrement was produced by a thermal manipulation which raises deep body temperature to a value of 38.5°C (101.3°F). In addition, although during the course of repeated exposures their subjects became heat acclimatized, they found no evidence of performance improvement over successive sessions with elevated body temperature. These results suggest independent elevation of body temperature up to 38.5°C (101.3°F), or approximately 1.3°C (2.4°F) over a mean value of 37.2°C (98.96°F), connotes the limit for the marginal impairment of mental performance. This observation is consistent with the limit observed in the mental and cognitive category as illustrated in Fig. 1.

In a recent set of experiments Allan, Gibson, and coworkers (1-3,14-16) have reported on the effects of skin and core temperature on a variety of tasks. In one study (14) they examined the specific effects of cycling deep body temperature values between 37.0° (98.6°F) and 37.6°C (99.68°F) on tracking ability. From their results they concluded that 37.6° C (99.68°F) represents a minimum core temperature value for degradation of a pursuit rotor tracking task. Further, they identified the critical level of deep body temperature above which performance of a rotary pursuit task is degraded is 37.6°-37.9°C (99.68-100.22°F). In light of the current interpretation, which proposes a tentative limit at 1.6°F (0.9°C) from a threshold derived in a time, temperature framework, the upper value of that proposed by Gibson and Allan (14) is consistent with previous observations on tracking performance decrement in thermal stress.

Although absolute values for the limit of completely efficient task performance are included for the three behavioral curves, and the physiological tolerance curve in Fig. 1, this is not to suggest that they are immutable thresholds. There are several factors which may affect the values which are proposed. Two of these, concomitant exercise and acclimatization through repeated exposure, may have a lesser effect than previously posited (13,26,41). The work of Mackworth and others (9,26) on heavy handle pursuitmeter performance in thermal stress has suggested tracking task performance impairment onset at time, temperature specifications well below those shown for the limitation of tracking in Fig. 1. However, the independent effect of heavy exercise on core body temperature was not monitored. Indeed, as noted, Mackworth measured body temperature at the end of performance tests only. Consequently it is impossible to match onset of task impairment with actual rise in deep body temperature. Concomitant exercise serves to increase the rate of rise of deep body temperature in thermally stressful environments. Therefore, collective results from heavy handle pursuitmeter tasks are not inconsistent with the interpretation of tracking performance impairment onset at approximately 1.6°F elevation of deep body temperature.

There is equivocal evidence concerning the effect of acclimatization on operator performance in extremes of heat. As previously noted Wilkinson, Fox, Goldsmith, Hampton and Lewis (41) found no mitigating effect for progressive acclimatization on a mental task performance. However, some investigators have found results which suggest the potence of such adaptation (10). An excellent graphical review of studies exhibiting acclimatization and no acclimatization may be found in the report of Ramsey, Dayal and Ghahramani (36). Although this factor clearly plays a role in long term performance at relatively mild temperature exposures (31), its exact impact on performance in extreme thermal transients has yet to be fully elucidated.

It may be observed that across the three behavioral tasks one factor, required response complexity, systematically increases. Thus the actual complexity of decision between a number of possible responses, and the motoric element necessary to accomplish that response, both increase from the mental to the tracking and from the tracking to the dual-task performance category. As can be seen from Fig. 1, this complexity appears to induce earlier heat stress related decrement.

As an operator becomes more skilled, and more familiar with task characteristics, the necessity to select between a number of possible responses is progressively obviated. Therefore, one factor which is posited as particularly influential upon the limit of performance efficiency under thermal stress is that of operator skill level. The suggestions that extreme heat differentially affects skilled and unskilled performers is implicit in the seminal observations of Mackworth (26)*. He noted that exceptionally skilled wireless telegraph operators barely increased their error rate, i.e., 2 to 6 errors, with an increase of 5°F, E.T. from 92° to 97°F, E.T. With the same temperature increase, a group classed as very good operators increased error incidence from 10 to 100 errors committed. Finally, with the same change in thermal conditions, competent operators produced a change in error rate from 40 to 175 errors. In the previous section on tracking efficiency the work of Nunneley and her coworkers (30) was assessed with respect to performance on a compensatory tracking task in elevated ambient temperature conditions. From Fig. 1 it may be noted that their time, E.T. specifications closely approximate those which would result in proposed performance decrement. However, their subjects were trained to plateau performance *before* the commencement of differential thermal performance exposures. It is possible that the skill level, as observed in the plateau performance, con-

*Although reprinted in Sinaiko, H. W. (Ed.), *Selected papers on human factors in the design and use of control systems.* Dover Publications Inc., New York, 1961. Mackworth's work was first collectively published in a Medical Research Council Special Report Series 268. H.M. Stationery Office, London, England, 1950. The experimental work was conducted initially during the period 1945-1947 at the instigation of the British Royal Navy.

tributed to the mitigation of temperature induced performance decrement. This observation finds support in the results of Blockley and Lyman (6) who noted that heat induced impairment onset in a simulated aircraft flight task was in part dependent on operator skill level.

Further evidence concerning performance and operator skill may be found in the work of Nunneley, Dowd, Myhre and Stribley (29). They reported the effect of two levels of heat stress, 29°C (84.2°F) and 32°C (89.6°F), E.T. (Corrected Effective Temperature) on a Repetitive Psychometric Measures battery. The results indicated that while learning was generally impaired on the battery of tasks, one sub-task, mental addition showed no effect for heat. Each of the other sub-tasks exhibited significant differential performance gains in heat and control exposures. It was suggested that impaired performance under thermal stress may be associated with new or emergency situations, in which previous operator practice would be limited.

The current synthesis implies coherence in results concerning task performance in extreme heat, when temperature, intensity and task category are specified. Within such differentiation, concomitant rises in deep body temperature may be noted as delimiting the onset of performance decrement in each group. Mitigation of such decrement may possibly be achieved by increasing operator skill. There are several experimental observations of such mitigation which as yet await further validation. As the differentiation of task content is achieved in a more detailed manner, apparently conflicting results of performance in more mild heat conditions may be integrated with results from intermittent tasks into an overall picture of performance in heat.

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