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Aviation, Space and Environmental Medicine, 52, 177-180.

Heat stress impairment of mental performance: A revision of tolerance limits

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HANCOCK, P. A. *Heat stress impairment of mental performance: A revision of tolerance limits.* Aviat. Space Environ. Med. 52(3):177-180, 1981.

A time-related, heat stress tolerance curve for unimpaired mental performance was constructed by Wing from a summary of 15 studies. The tolerance limits, more properly described as the lower limits for heat impaired mental performance, were subsequently adopted by the National Institute for Occupational Safety and Health as the recommended standard of tolerance times for sedentary work in heat stress. Although Ramsey and Morrissey have reported a series of isodecrement curves which indicate that mental performance impairment in heat may not be a simple function, a reappraisal of the upper limit for unimpairment has not yet been advanced. The present review reevaluates results of early studies, apparently supportive of Wing's position, and proposes an alternate interpretation. Further, analysis of more recent data suggests a mental performance impairment/heat stress relationship closely related to human thermophysiological tolerance limits.

WHILE the physiological effects of heat stress on the human are well understood, confusion still surrounds concomitant psychological effects. This is due in part to the failure of experimenters to standardize procedures and to specify the levels of heat stress imposed (9). The conflicting evidence produced has, in part, fostered acceptance of the tenet that heat stress degrades mental performance some time *before* physiological tolerance limits are reached. Wing (19) supported this belief by constructing a curve based on seven data points adduced from five studies reporting the onset of time-related mental performance decrements in thermally stressful environments.

MATERIALS AND METHODS

Three points which constitute the extreme heat stress portion of the curve are derived from the work of Blockley and Lyman (2). Eight Naval and civilian aircraft pilots performed two mental tasks—number addition and numerical comparison—in estimated Effective Temperatures of 38.1°C (100.5°F), 42.8°C (109°F) and 45.6°C (114°F). Effective Temperature (E.T.) is an index of environmental heat which synthesizes dry bulb temperature, relative humidity, and air movement (8). Exposure score was subtracted from a comfortable (80°F, dry bulb temperature) preexposure control. The mean difference derived, expressed as a function of the physiological tolerance of each subject, was used to calculate significant improvement and decrement in performance (Table I).

RESULTS AND DISCUSSION

In his analysis, Wing (18) utilized only the addition task, rejecting the comparison task as relatively heat-insensitive. From these data, he selected initial points of performance decrement. At the lowest temperature, 38.1°C (100.5°F) he reported the decrement as being 60% through the 72.5-min exposure, that is at 43.5 minutes (19). However, as inspection of Table I indicates, this point represents significant *improvement* in performance and not decrement. Significant decrement is found only during the last performance periods for addition, checking, and combined scores at this temperature.

At the intermediate temperature, 42.8°C (109°F), Wing cites Lyman's (10) observation that one subject's preexposure score was atypically low in comparison with his previous efficiency. Eliminating this subject produced significant impairment 50% through the 36-min exposure. Parenthetically, it may be noted that the elimination of an alternate subject produced significant decrement at this point, whilst yet another subject who made over 30% of the studies' total errors may be legitimately regarded as the atypical participant. Blockley and Lyman (2) accounted for the absence of decrement at

An earlier version of this paper was presented at the 24th Annual Meeting of the Human Factors Society, Los Angeles, CA, on Oct. 16, 1980.

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TABLE I. ADAPTED FROM BLOCKLEY AND LYMAN (2) CHANGES IN SCORE DURING EXPOSURE (PRE-EXPOSURE SCORE MINUS EXPOSURE SCORE)

Percentage of Exposure Period	Addition Mean Diff.	Addition S.E.M.	Addition t Ratio	Checking Mean Diff.	Checking S.E.M.	Checking t Ratio	Combined Mean Diff.	Combined S.E.M.	Combined t Ratio
(a) — 160°F (100.5°F, E.T.) for 72.5 min									
1st							4.75	1.90	2.50
.25	.25	1.75	0.14	−2.00	2.18	0.92	−1.75	2.62	0.67
.50	−1.62	1.71	0.95	−0.75	3.43	0.22	−2.38	4.07	0.58
.60	−3.38	0.94	3.57*	−5.13	4.34	1.18	−8.50	4.29	1.98
.75	2.50	2.11	1.18	3.50	3.45	1.02	5.62	4.07	1.38
.80	1.75	2.11	0.83	4.13	3.35	1.23	5.88	4.02	1.46
Last	5.12	1.72	2.98	7.38	2.30	3.21	12.38	1.98	6.24**
(b) — 200°F (109°F, E.T.) for 36.0 minutes									
1st							3.25	2.90	1.12
.25	1.25	2.02	0.62	2.38	2.21	1.07	3.62	3.25	1.12
.50	−2.25	1.80	1.25	−0.62	2.49	0.25	−2.88	3.72	0.77
.75	0	2.03	0	−3.00	2.56	1.17	−3.00	3.36	0.89
Last	0.75	1.97	0.38	4.37	2.02	2.16	5.25	3.51	1.49
(c) — 235°F (114.0°F, E.T.) for 24.0 minutes									
1st									
.25	6.50	2.37	2.74	3.12	3.78	0.82	9.63	5.78	1.66
.50	1.88	1.84	1.02	0.87	3.89	0.22	1.75	5.19	0.34
.75	4.87	1.12	4.34*	4.00	3.85	1.04	8.88	4.43	2.00
Last	7.25	1.78	4.07*	9.00	2.90	3.10	16.38	4.10	3.99*

Underlined value = $p < 0.02$; * = $p < 0.01$; ** $p = < 0.001$.

this temperature by suggesting that peak stress and peak incentive act to offset performance depression at 36 min, the time duration of this exposure.

At the highest level of heat stress, 45.6°C (114°F), significant decrement first occurs 25% through the 24-min exposure. In using this point, Wing failed to account for a subsequent 6-min performance period in which no significant performance change from a pre-exposure control was exhibited. A curvilinear description of the upper limits of unimpaired mental performance in heat, as proposed by Wing, implies decrement in time periods subsequent to the limit suggested. As inspection of Table I shows, this is not supported by the data of Blockley and Lyman (2). The present paper proposes decrement occurring at 66 min (the midpoint of the final two intervals in Table I) for the lowest temperature 38.1°C (100.5°F) and at 18 min for the highest temperature, 45.6°C (114°F). The equivocal nature of the data at the intermediate temperature, 42.8°C (109°F), prevents a time point from being established.

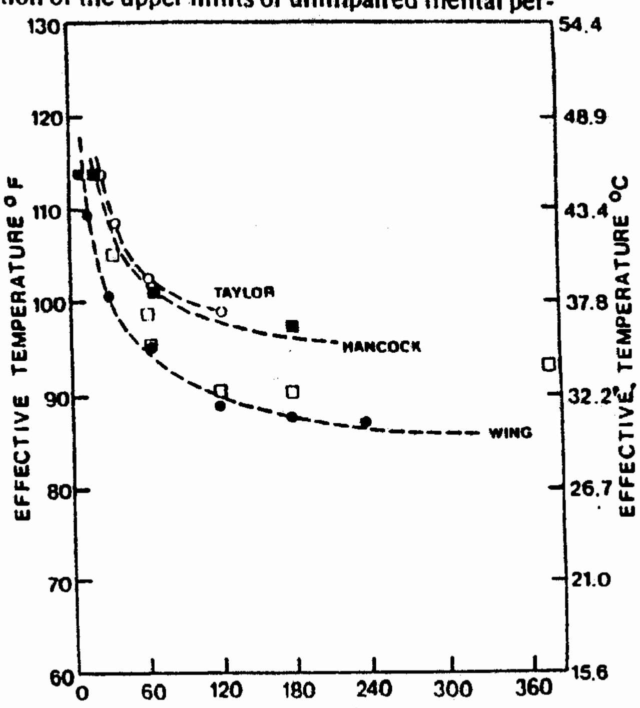

Fig. 1. Physiological tolerance (Taylor), unimpaired mental performance (Hancock, Wing) curves, and effective temperature.

Fig. 1 presents Wing's original curve and a marginal physiological tolerance curve reported by Taylor (15). Superimposed is a curve derived from the present paper labelled "Hancock." The reinterpretation of the Blockley and Lyman work is represented by the two filled squares on the latter curve. Also presented are open-square symbols each of which represents a different study reporting no decrement in mental performance above Wing's tolerance limit.

Fig. 2 amplifies data from the studies which show no performance decrement above Wing's limit and which support the present reinterpretation. Each experiment consists of one or more test temperatures indicated by circles. Above each study are letters which represent the task undertaken, these are explained in the included legend and beneath each experiment are letters referring to study authors.

The remaining four points which constitute Wing's curve are additionally open to reinterpretation. In the absence of reported decrement for a 60-min exposure up to E.T. 33°C (91.5°F), (1,4), Wing utilized his own study to establish an E.T. 35°C (95°F) threshold for a 1-h period. In this study, Wing and Touchstone (20) presented lists of English words which were repeated every 10 min for 1 h. Successive recall, after each presentation, was tested under heat stress conditions of E.T. 22.2°C (72°F), E.T. 32.2°C (90°F), and E.T. 35°C

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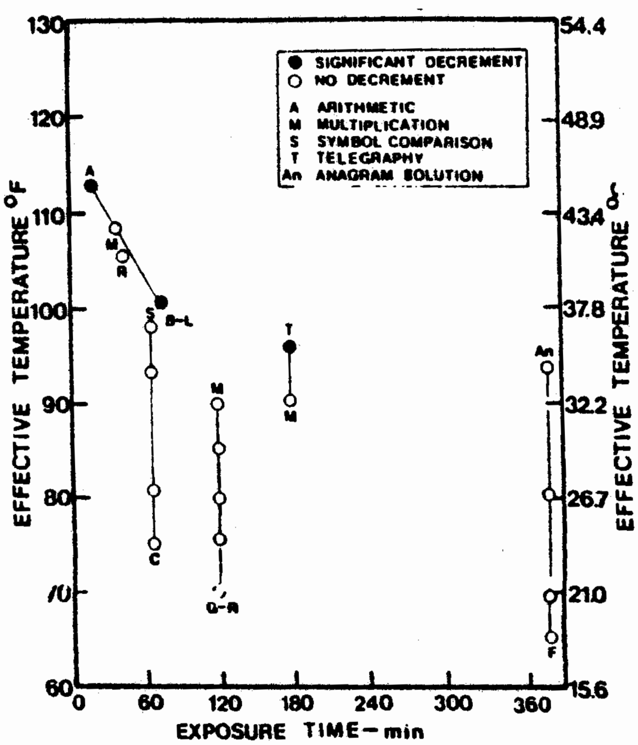

Fig. 2. Performance and effective temperature.

(95°F). Significant recall decrement was found at 35°C compared to each of the two lower temperature conditions. However, this main effect for temperature was noted on the first recall trial after only 10 min of exposure. In the absence of a time by temperature interaction, results suggest impairment onset lies not at the 1-h limit but below the 10-min period for this E.T. 35°C. Clearly this observation supports neither Wing's original position nor the current interpretation of mental performance impairment in heat stress.

A more important criticism, at this point, concerns Wing's use of Chiles' (4) study to support his case. In that study, the effect of a variety of heat stress levels was investigated on a complex symbol matching task. Although Wing correctly summarized the results of the Chiles' first experiment, he erroneously utilized data from Chiles' second experiment as supportive of his position. The latter experiment reports *no* decrement in performance at E.T. 36.7°C (98°F), not E.T. 32.8°C (91°F), as Wing stated. This point is included as an open-square symbol in Fig. 1 at 60 min and is extended in Fig. 2 to include the result of no decrement at E.T. 34.4°C (94°F) given by Chiles (4).

For a 2-h exposure, an interpreted point at which decrement would first occur is inferred by extrapolation in a study by Carpenter (3) at E.T. 31.7°C (89°F). A more recent study by Givoni and Rim (6), using five figure multiplication, reported no decrement in performance at this temperature. Wing criticized the statistical procedure in the latter study and attempted to rework the data to account for a practice bias. Although he effectively failed to do this and examined only output regardless of errors, Wing stated that his reanalyses of these data lend support to the assumption of impairment onset at this time/temperature combination. Conversely, Givoni and Rim (6) had concluded that these data support the suggestion that man is able to maintain his maximal degree of mental performance even in hot environments, provided that he is stimulated enough by incentives or otherwise. The present reviewer agrees with the latter interpretation in suggesting little mental performance decrement before imminent physiological collapse.

The 3-h limit is derived from the work of Mackworth (11). Eleven experienced operators performed a telegraphic reception task in five ascending levels of heat stress. Performance errors during the exposures were recorded in two ways. First, any message with five or more content mistakes was classed as an error in reception. Second, a mean number of individual letter, omission or numerical mistakes per subject per session was recorded. Using the first and more gross measure, Wing placed decrement at E.T. 30.9°C (87.5°F) for this 180-min exposure. Mackworth noted the conservative estimate of E.T. 32.2°C (90°F), based on a curve-fitting procedure, for impairment onset at this time point, but also cited a "statistically definite" rise in error score at E.T. 87.5°F. It is difficult to establish a precise temperature from the data of Mackworth; therefore both the lower limit, indicating no decrement, and the upper limit, indicating decrement, are reported in Fig. 1 and 2.

The final point on Wing's curve is established at the 4-h limit. This point represents results from the study of Viteles and Smith (16), who attempted to determine the effects of heat and noise on the efficiency of personnel working in a bridge chart room aboard a sea-going destroyer. Questions were posed around problems of mitigating cooling support, which was costly in terms of payload and high in noise level, compared to little thermal mitigation and the possibility of concomitant performance deterioration. All data collected by Viteles and Smith was with a minimum of 72 dB background noise level. The effect of a single stressor is unclear; the action of compound stressors is perhaps an even more complex picture (7,17). It is doubtful if these data should be used to support a curve representative of mental performance impairment in heat alone. However, it is interesting to note that, although output was reduced as temperature increased, the number of errors in mental multiplication did not rise with heat in this study.

There remain two studies, included in Fig. 1 and 2, which report no decrement in mental performance above the limit proposed by Wing. In 1975, Ramsey, Dayal, and Ghaharamani (13) investigated the effects of three levels of heat stress on sedentary tasks. One task concerned mental multiplication of sets of three by four digits, which was scored on speed and accuracy as assessed by correct digits in each line of multiplication and each column of addition. Although Ramsey *et al.* (13) noted that after performance in highest heat stress subjects were physically exhausted, they found no performance decrement for a 45-min exposure at this level, approximately E.T. 40°C (104°F). Finally, in a study lasting over 6 h, Fine, Cohen, and Crist (5) asked subjects to solve anagrams in E.T. 33.9°C (93°F). They concluded that no decrement or increment in mental performance could be attributed to either high temperature or high humidity for this 380-min exposure period.

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However, the unusual nature of the task may have contributed to the observation of no decrement at this temperature.

This review of mental performance in heat stress suggests that decrement in mental task proficiency is a function of imminent thermophysiological collapse. This position is in direct contrast to the statement by Wing (19) that the temperature duration curve for mental performance lies well below a comparable physiological tolerance curve at every point in time. In constructing his curve, Wing attempted to produce a useful function from available data on impairment onset, not all of which was readily interpretable within a time/temperature framework. His function was subsequently adopted by the National Institute for Occupational Safety and Health (12) as the National Standard for sedentary work performance in heat. From the present review, which indicates a much higher absolute level for impairment, the NIOSH standard contains a safety margin at each time exposure wherein increased temperature may be tolerated without statistical impairment of performance.

The current curvilinear description may be robust in terms of morphology although susceptible to alteration in absolute level from various factors. Among these, acclimatization, subject motivation, and specific task motor skill may serve to elevate the curve, while concurrent exercise and increasing task response complexity may act to depress the curve, reducing the absolute level at which decrement would first occur. This possibility is indicated in Fig. 1 by showing curves composed of dashed lines rather than solid, immutable time/temperature relationships.

Assessment of human performance under heat stress has and continues to be of practical importance in the fields of commerce, aviation, and space technology. Under a variety of conditions, the human operator may be required to monitor and manipulate complex machines with little or no mitigating thermal support. Although the current review suggests only a slight mental performance decrement before impending physiological collapse, most control situations require constituents of motor performance more susceptible to heat. A description of the relationship between such psychomotor elements and onset of impairment induced by ascending heat stress is necessary to ensure the optimal functioning of many man/machine systems and requires further experimental work.

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