COMPLEX PERFORMANCE DURING EXPOSURE TO HIGH TEMPERATURES

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I. Introduction.

A number of advances achieved during the past two decades in the field of aviation and space flight have led to an increased requirement for more precise information concerning the effects of elevated temperatures on man's performance capabilities. For the most part, the questions raised by these advances stem directly from the increased speeds of which aircraft and space vehicles are capable. Although normal operation of aircraft does not entail exposing the man to very great heat loads, in emergency situations cabin temperatures may rise to extreme values if the cooling system should fail and adequate back-up cooling capability is not provided. Techniques that are adequate to provide temporary or even long-term protection to individual crewmembers (e.g., a ventilated suit) are not feasible for passenger-carrying aircraft and certainly not applicable to commercial operations.

The potential temperature problems become extreme in the supersonic transport in which the safety and (at least to some extent) the comfort of 200 or more people must be protected. The U.S. SST has been designed to fly in the regime of 1,875 m.p.h. and 70,000 feet. Under these conditions, the surfaces of the plane can achieve steady-state temperatures of 260° C. (500° F.)[5]. Clearly, this implies a significant weight penalty (for insulation and cooling) if the interior of the aircraft is to be maintained at temperature levels that will neither impair the performance of the crew nor endanger passengers whose states of health have in no way been certified. The critical question is, how much of this weight penalty must be duplicated to cover the possibility of failure of the primary cooling system? The answer to this question must be applicable, not only to aircrew of rather diverse composition with respect to age and general physical condition, but also to the general population including the very old, the very young, and the infirm. However, to keep the magnitude of the problem within manageable proportions for research purposes, we will be concerned here only with aircrew performance.

A number of previous investigations have yielded data that are relevant to the problem as herein defined. Wing[10] has reviewed those studies in which the primary or exclusive emphasis was on mental performance; the conclusions of his review are shown graphically in Figure 5, and they will not be discussed further at this point. A similar review is not available for motor performance, and, therefore, we shall cover that topic briefly.

Forlando, Barmach, and Coakley[4] have reported a study in which simple reaction time showed no decrement after 6 hours under a temperature condition of 47.2° C. (117.0° F.) db/29.4° C. (85.0° F.) wb (dry bulb/wet bulb). Similarly, Loeb and Jeantheau[6] found no significant loss in performance on a task of monitoring 20 dials over a 3-hour period under a heat stress that was allowed to vary between 43.3° C. (110.0° F.) and 51.6° C. (124.9° F.) (wet bulb not specified). Crocker and Waitz[3] found reaction time to be slower during a 15-minute exposure to 149° C. (300° F.) and "low humidity." However, they indicated that they felt the decrement to be too small to be of any practical importance.

Tracking tasks have generally proven to be somewhat more sensitive to the effects of high temperatures. Teichner[9] measured performance on a pursuit rotor during a 30-minute trial at effective temperatures of 21.1° C. (70° F.), 29.4° C. (85.0° F.) and 37.8° C. (100.0° F.). He found a significant drop in time-on-target at the two higher temperatures. Blockley and Lyman[1] measured the performance of subjects in flying a repetitive, 4-minute pattern in a Link trainer at three temperatures: 71.1° C. (160° F.), 93.3° C. (200° F.) and 112.9° C. (235° F.); the estimated effective temperatures were 37.8° C. (100° F.), 42.2° C. (108° F.) and 45.0° C. (113° F.) respectively. Testing continued until the subject showed signs of approaching his physiological tolerance limit as indicated by an unacceptable rise in rectal temperature. The mean times to tolerance were 61 minutes, 29 minutes, and 21 minutes respectively. Blockley and Lyman state that error began increasing abruptly approximately 8 to 12 minutes before the runs were terminated. Error was measured as a composite involving accuracy of holding altitude, heading and airspeed. Pepler[8] used a one dimensional tracking task of pointer alignment during two 30-minute exposures to a temperature condition of 46.6° C. (115.9° F.) db/40.6° C. (105° F.) wb, a condition said by Pepler to yield an effective temperature equivalent to the 93.3° C. condition used by Blockley and Lyman. A significant increase in error was reported to appear at 5 to 6 minutes after the beginning of the period and a marked rise in error occurred at approximately 20 minutes.

Based on the data summarized by Wing and those just outlined, the effective temperature to which a man can be exposed for a period of 30 minutes without some impairment in his performance may be as low as 29.4° C. (85° F.) (Teichner) or as high as 37.8° C. (100° F.) (Blockley and Lyman).

In any event, the studies cited here, as well as those reviewed by Wing, suffer from two major deficiencies with respect to the problem of setting a maximum temperature figure for commercial aircraft operations. First, the subjects used in the studies were young, healthy, and (in at least some cases) acclimatized to high temperatures. Second, the tasks (with the exception of the Blockley and Lyman study) in no way approximated the range of activities required of a crewmember in operating an aircraft. In particular, the requirement for time-sharing a variety of tasks was not included in these studies, a fact which substantially decreases the applicability of the resultant data. Although the procedure used by Blockley and Lyman involved a complex task (flying a Link trainer), the scoring method was somewhat lacking in precision.

Clearly, additional research is required if the allowable temperature/time profile for commercial aircraft operations is to be accurately specified. The purpose of the study reported here is to make a contribution toward filling the gaps in our knowledge of this problem area by (1) examining two additional temperature conditions in the range suggested by the literature to be critical; (2) using a sample of subjects who are both trained as pilots and representative of the age range of commercial airline pilots; and (3) requiring performance of a complex task designed to assess functions involved in operating an aircraft and requiring the exercise of those functions in a time-shared manner.

II. Methodology.

Subjects. The subjects used in all phases of the study were FAA Aeronautical Center male employees who volunteered to participate in a high temperature study in response to an item in the Center information bulletin. No attempt was made to select the subjects according to number of hours flown, type of rating, or physical characteristics, except that all subjects held private or commercial pilot's licenses and all held current Class II or III Medical Certificates. The total number of subjects was 30; their ages ranged from 30–51.

Physiological Measures. The physiological parameters monitored (in each case at 2-minute intervals) were: rectal temperature via thermistor probe and YSI Telethermometer; heart rate by chest electrodes and Grass Model 5C recorder; and skin temperature by a Honeywell Elektronic 16 recorder with thermocouples on forehead, tip of index finger, and back of hand.

The complex performance device, shown in Figure 1, was designed to measure performance of five tasks. These are: two dimensional compensatory tracking, mental arithmetic, meter monitoring, discrimination reaction time, and simple reaction time.

The tracking task is presented to the subject on a CRT display 4¾ inches in diameter (designated as A in Fig. 1). Intersecting horizontal and vertical lines etched into a clear plastic overlay define the two principal axes. The controlled element is a dot of light approximately 1 mm. in diameter. Control is exercised by manipulation of a hand control stick (designated as A_1 in Fig. 1). The stick gain is such that movement of the stick approximately 25° from vertical is sufficient to move the dot off the face of the display. A 15° movement of the stick is sufficient to compensate for the maximum displacement that the forcing function can produce.

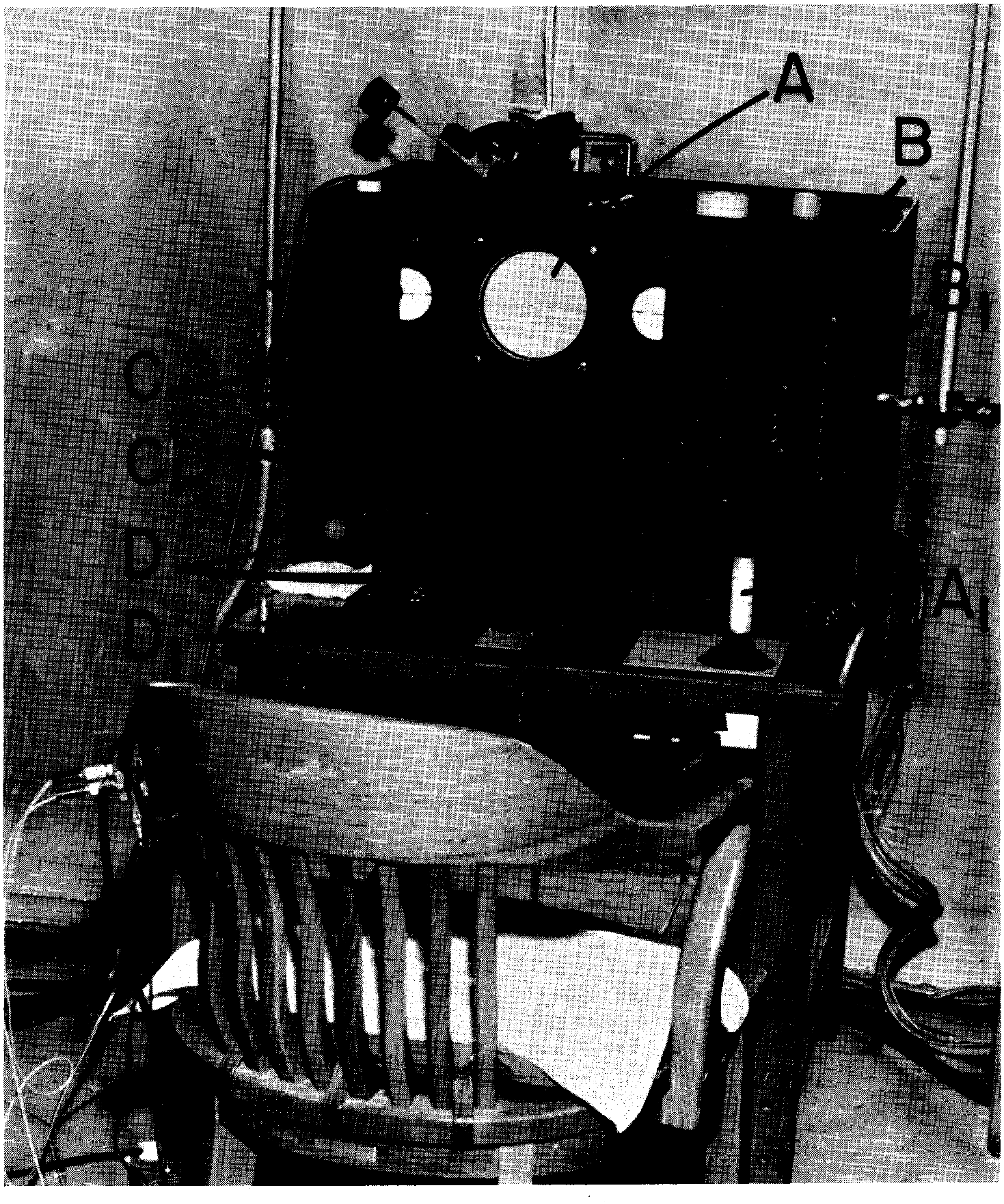


FIGURE 1—Complex performance device. (See text for identification of components.)

The forcing function for the tracking task is generated by selecting "at random" from among eleven possible voltages—five minus voltages, five plus voltages, and zero volts. The selection is carried out by a stepping switch actuated once each 4 seconds, the various contacts of the switch being wired to the 11 positions of a voltage divider by reference to a table of random numbers.

The output of this circuit, which is a series of step-function changes in voltage, is modified by an operational amplifier circuit into which is built a lag circuit and two stages of integration before being displayed to the subject. The disturbances are programmed independently for the two axes so that the dot appears to the subject to wander about the display at random. The polarity of the voltages applied to the stick are such that forward movement of the stick causes the dot to move down and movement of the stick to the right causes the dot to move to the right. The output of the stick goes through one stage of integration before being added to the output of the forcing function generator; thus, from the subject's point of view, he is not manipulating a simple position control.

Four measures were recorded of the subject's performance of the tracking task: integrated absolute error in the horizontal and the vertical dimensions (taken independently) and integrated error squared in the horizontal and vertical dimensions (also taken independently). From the subject's point of view, error is the deviation of the dot from the intersection of the two axes scribed on the plastic overlay. These measures were recorded at the end of each minute of performance; thus, because of the time required to read and reset the scoring integrators, four 1-minute samples of performance were measured for each 5 minutes of tracking. However, the subject had no way of knowing that there were brief periods during which his tracking performance was not being measured.

The mental arithmetic task is presented to the subject by means of three in-line projection displays designated as B in Figure 1. A two-digit number appears in the first window and, simultaneously, a buzzer sounds to alert the subject. The subject notes and remembers the number and acknowledges seeing it by pressing a button immediately below that window. The first number then disappears and a two-digit number appears in the second window and the buzzer again sounds. The subject acknowledges this number in a similar manner whereupon that number also disappears. The subject is instructed to add this number to the first and remember their sum. A two-digit number then appears in the third window; the subject is instructed to subtract this number from the sum of the first two numbers. He enters his answer into two columns of push-buttons designated as B_1 in Figure 1. He is also instructed that, as soon as he has entered his answer, he is to push a button immediately above the "tens" answer column to indicate that his answer is complete. Problems are presented on this task at a rate of approximately three/minute. Performance was measured in terms of percentage correct and the time (to the nearest 1/100th second) from the appearance of the third number until the subject pushed the "answer complete" button.

The meter monitoring task is presented to the subject by means of the two meter displays designated as C in Figure 1. The normal condition for the two displays is for the two pointers to be at rest in the horizontal position; the left meter points to the 3 o'clock position, the right to 9 o'clock. Introduction of a "signal" results in the drifting of one of the pointers either up or down through an angle of approximately 20 degrees. The subject indicates that he has detected a meter signal by pushing the appropriate button (designated C_1 in Figure 1); he pushes the left button for the left meter and the right button for the right meter. A correct response "freezes" the pointer in its current location and illuminates an amber-colored light above the affected meter, thus giving immediate feedback to the subject. A signal, if undetected, produces the maximum 20-degree deflection in approximately 8 seconds, at which time it rather quickly returns to the normal position. This return to normal is of sufficient attention value that subjects often notice it and are made aware that they have missed a signal. Signals are introduced at a rate of approximately 1.5 signals/minute. The meter affected and the direction of the deflection (up or down) is selected unsystematically. Performance was measured in terms of the response time to the nearest 1/100th second and the number of signals detected.

The simple reaction time task requires the subject to respond to an amber-colored light located on the lower left corner of the panel (designated in Fig. 1 as D) by depressing a push-button located in the top of the control stick for the tracking task; the response extinguishes the light. Signals are presented on this task at a rate of approximately one signal every two minutes. The performance measure used was the time elapsed (to the nearest 1/100th second) from the onset of the light until the switch was actuated to turn the light off.

The discrimination reaction time task consists of two lights located on the lower right corner of the panel (designated as D in Fig. 1) and two telegraph keys located immediately below the lights. The left light and key are green; the right light and key are red. The subject is required to use his left hand in responding to this task and to keep that hand on a third "ready" key (located on the table just to the left of center near the front edge) except when responding to this or one of the other tasks. The subject depresses the green key in response to a green light and the red key in response to a red light. Signals are presented at a rate of approximately two/minute. Two basic time measures were recorded on this task and a third measure was derived from the first two. Time was measured to the nearest 1/100th second from the onset of a red (or green) light until the subject lifted his hand from the ready key. The elapsed time from the onset of a light until the depression of the appropriate response key was also measured. From these two measures—reaction time and total time—a third measure was derived by subtracting the first from the second to yield an index of movement time.

These five tasks are presented in three different combinations so that the levels and natures of the workloads imposed on the subject can be varied. The first combination, designated as condition A, consists of the tracking task, simple reaction time task, discrimination reaction time task, and meter monitoring. The second combination (condition B) consists of those tasks constituting condition A plus the mental arithmetic task. And the third combination (condition C) is the same as condition A except that the arithmetic task is substituted for the tracking task. During all conditions, the subjects respond only to the tracking task and the simple reaction time task with the right hand; they respond to all other tasks with the left hand and are instructed to keep the left hand on the ready key when not responding to one of these tasks.

Environmental Chamber. The chamber in which the performance console was located and all of the training and testing were carried out was 10 feet long, 8 feet wide, and 8 feet high. The interior was illuminated by a single 300 watt light bulb located in the center of the ceiling. The subject sat on a padded, wooden chair with his back toward both the entrance door and the viewing window located beside the door. He was dressed in a short-sleeved, loose shirt, trousers, shoes and socks.

The temperature of the chamber was controlled by two methods. The primary system provided a convective input that controlled air temperature directly. However, this system by itself was incapable of achieving the desired temperature rises as rapidly as was required. Therefore, an auxiliary system of six, 5 kw. radiant heaters was used to bring the temperature up to the specified value. Once the temperature had stabilized, only one or two auxiliary heaters were typically required to maintain equilibrium. Control of humidity was completely automatic. The convective system produced a continuous flow of turbulent air varying between 50 and 100 ft./min. at the subject position at all temperatures.

The temperature conditions used were as follows:

Phase I—60.0° C. (140° F.); vapor pressure 13.6 mm. Hg, relative humidity 9.1%

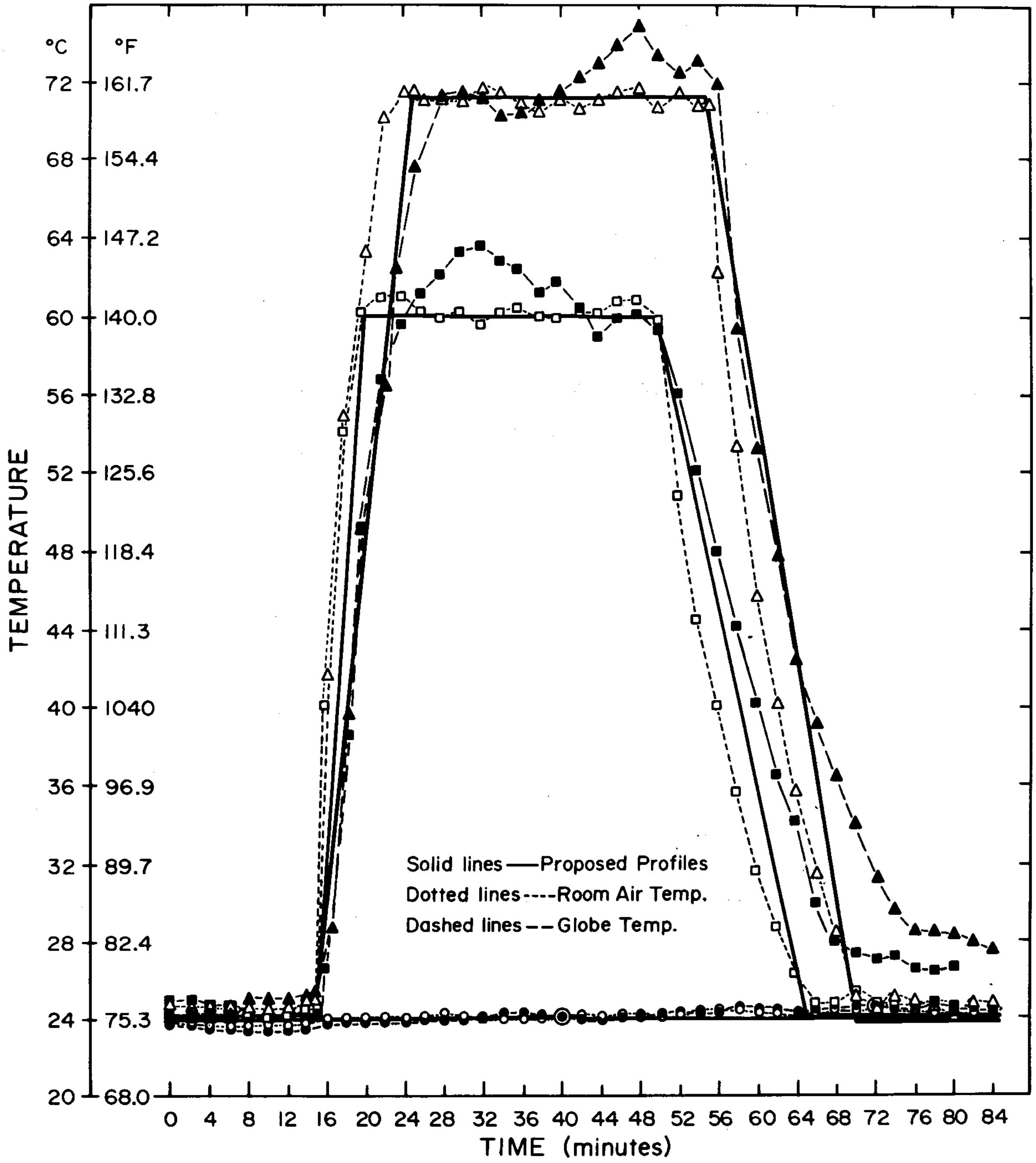
Phase II—71.1° C. (160° F.); vapor pressure 19.9 mm. Hg. relative humidity 8.5%

Phase III—23.8° C. (75° F.); vapor pressure 2.6 mm. Hg, relative humidity 12.0%

The temperature conditions of Phase III were maintained during training and during the pre- and post-exposure baseline periods of Phases I and II.

Temperature was monitored by means of an air probe located just above and to the right of the subject's head. Subsequent checks showed that the Globe temperature at the level of the subject's trunk approximated the air temperature (Fig. 2).

Procedure. Twenty subjects served in Phase I of the experiment which involved a 30-minute exposure to a temperature of 60° C. The subjects reported to the Laboratory the afternoon before they were to be tested. They were given a brief indoctrination as to the purposes of the experiment, the conditions to be used, and the safety precautions being taken. They were then



A B C B B A B C A B C B B B A B C

Schedule of performance tasks sequence for the 23.8° C (75° F) and the 71.1°C (160° F) exposures.

A B C B A B C A B C B B B A B C

Schedule of performance tasks sequence for the 60.0° (140° F) exposure.

A = Tracking, monitoring. B = Tracking, monitoring, arithmetic. C = Monitoring, arithmetic.

FIGURE 2—Protocol of experiment. Proposed and actual air temperature profiles (23.8°, 60.0°, 71.1° C.) are indicated as well as black globe temperature. Task combinations are indicated by A, B, C. Each task combination was performed for five minutes. Baseline data were collected during pre-exposure period.

given a description of the tasks and were told how to perform them. The first training trial consisted of 15 minutes of performance with five minutes of each of the task combinations in the sequence A, C, B. After a short rest, this was followed by 15 minutes of performance of the combinations in the sequence A, B, C. After another rest period, the subjects performed for 30 minutes (A, B, C, A, B, C); another rest period followed and then this 30-minute sequence was repeated.

Subjects reported to the Laboratory at approximately 8:30 on the morning of the test. The first 20 minutes were spent in attaching the physiological recording electrodes to the subject and in verifying the adequacy of the electrode placements for recording purposes. The subject was then equipped with a handtowel tied comfortably around his forehead to serve as a sweatband. Preliminary exposures had shown that profuse sweating could be expected and, as a result, vision would likely be interfered with. Inasmuch as the purpose of the experiment was to examine the integrity of performance functions, it was decided that such a readily preventable effect of the heat should not be permitted to interfere with the primary interest of the research. Figure 2 shows the protocol for the experiment. The first 15 minutes were devoted to collecting baseline data and involved the three performance conditions in the sequence A, B, C. Beginning with the 16th minute, the chamber heat sources were activated and the temperature was stabilized at 60° C. by the end of the 20th minute. During the period when the temperature was increasing, subjects performed on task combination B, the heaviest workload condition. The period at temperature consisted of two repetitions of the A, B, and C sequence. At the end of the 50th minute the process of lowering the temperature began so that it would return to normal (23.8° C.) by the end of the 65th minute; during this period of decreasing temperature, the subjects again performed on task combination B. Upon reaching normal temperature, the subject began a 15-minute period of post-exposure testing, after which the run terminated.

During Phase II, 11 of the 20 Phase I subjects were tested during a 32-minute exposure to 71.1° C. The afternoon before the test, the subjects came to the Laboratory for 45 minutes of refresher training. The following morning, the subjects were tested according to the same basic schedule with the exception that, since it required 7 to 8 minutes to reach the higher temperature, the 15-minute baseline period was followed by 10 minutes of performance of condition B. Thus, the total time at temperature was approximately 32 minutes, and the total period of testing was 85 minutes.

A new sample of 10 subjects was tested in Phase III. These subjects were given the same training as the subjects in Phase I and were tested according to the schedule used in Phase II except that the temperature was maintained at 23.8° C. throughout the 85-minute test period.

III. Results.

Physiological Responses. Rectal temperatures during the Phase I experiment (60° C.) increased 0.3° C. (0.5° F.) to a peak of 37.7° C. (99.9° F.) which was reached approximately on the first reading made after the chamber temperature had returned to "normal." As shown in Figure 3, rectal temperature did not begin to rise until 10 to 20 minutes after chamber temperature began to increase. Rectal temperatures during Phase II (also shown in Fig. 3) rose 0.6° C. (1.1° F.) and reached a peak of 38.05° C. (100.5° F.). As in Phase I, the peak rectal temperature occurred during the post-exposure period. It had virtually reached the peak approximately 10 minutes after the air temperature began to decrease and stayed at about that value until about 5 minutes after the chamber temperature had reached normal. During Phase III (23.8° C.) rectal temperature decreased 0.2° C. (0.4° F.) to a value of 37.2° C. (99.0° F.) during the course of the run.

Heart rate (Fig. 3), during exposure to 60.0° C. reached a mean peak of 114 beats/min.; the highest value was recorded during the last minute of heat exposure, i.e., just before the temperature began to decrease. Peak heart rate during exposure to 71.1° C. was 132 beats/min. with the peak occurring during the first minute of the period during which the temperature was lowered. In both Phases I and II, heart rate began to increase as soon as the chamber temperature began to rise, and in both experiments, heart rate had returned to essentially pre-exposure levels by the end of the run. During the Phase III experiment, heart rate remained essentially unchanged during the entire run.

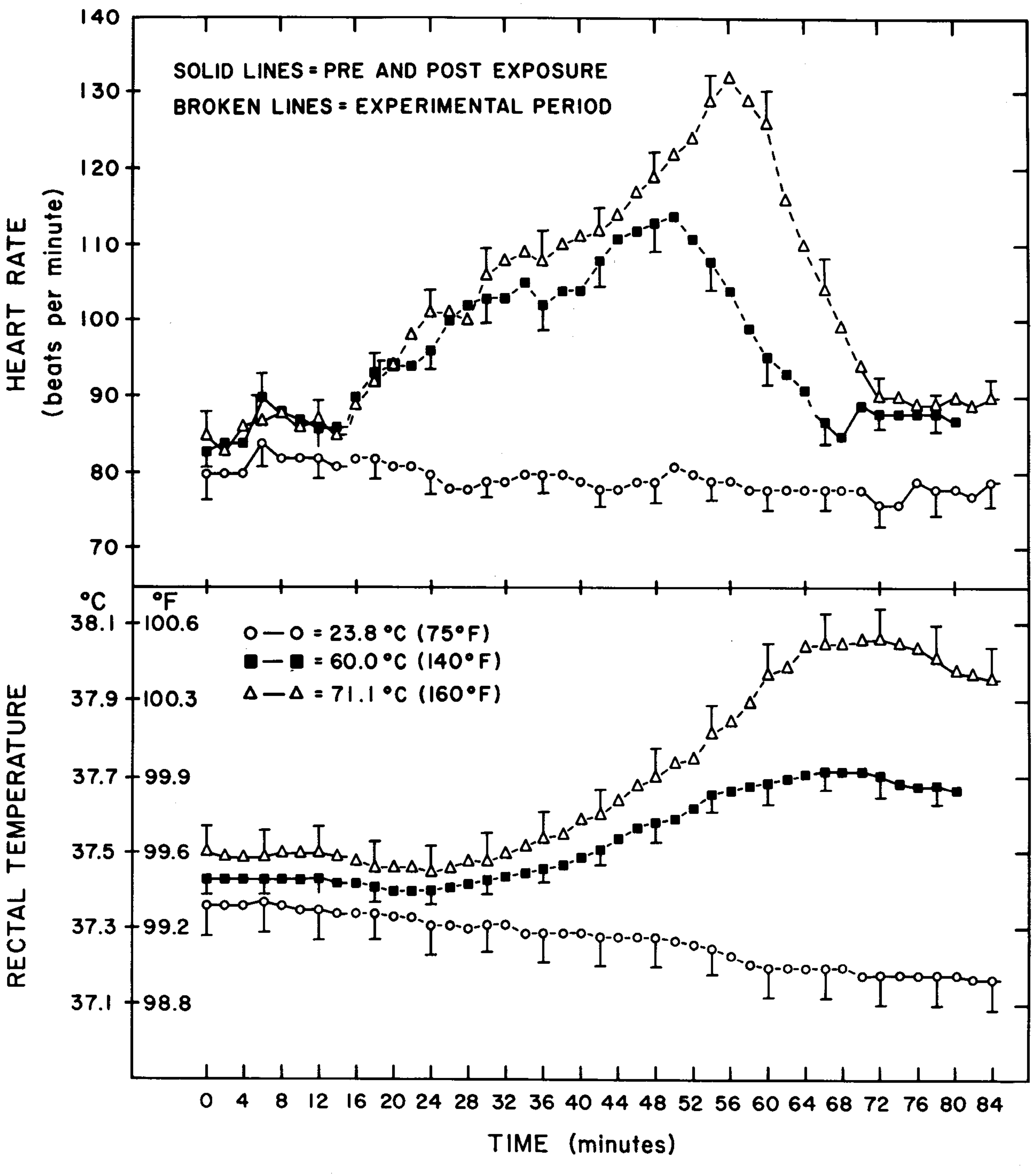


FIGURE 3—Heart rate and rectal temperature during exposure to 23.8, 60.0 or 71.1° C. Values are means with standard error shown at six-minute intervals.

Body surface temperatures (Fig. 4) increased rapidly during the first minutes of exposure to heat and then remained level or increased slowly during the remainder of the exposure. At 71.1° C., forehead temperature reached 40.7° C. (105.3° F.); hand temperature was 40.2° C. (104.4° F.); and finger temperature was 42.1° C. (107.8° F.). At 60.0° C., skin temperatures, in the same order were 39.2° C. (102.5° F.), 38.9° C. (102.0° F.), and 40.9° C. (105.6° F.). During exposure to 23.8° C., all temperatures were unchanged.

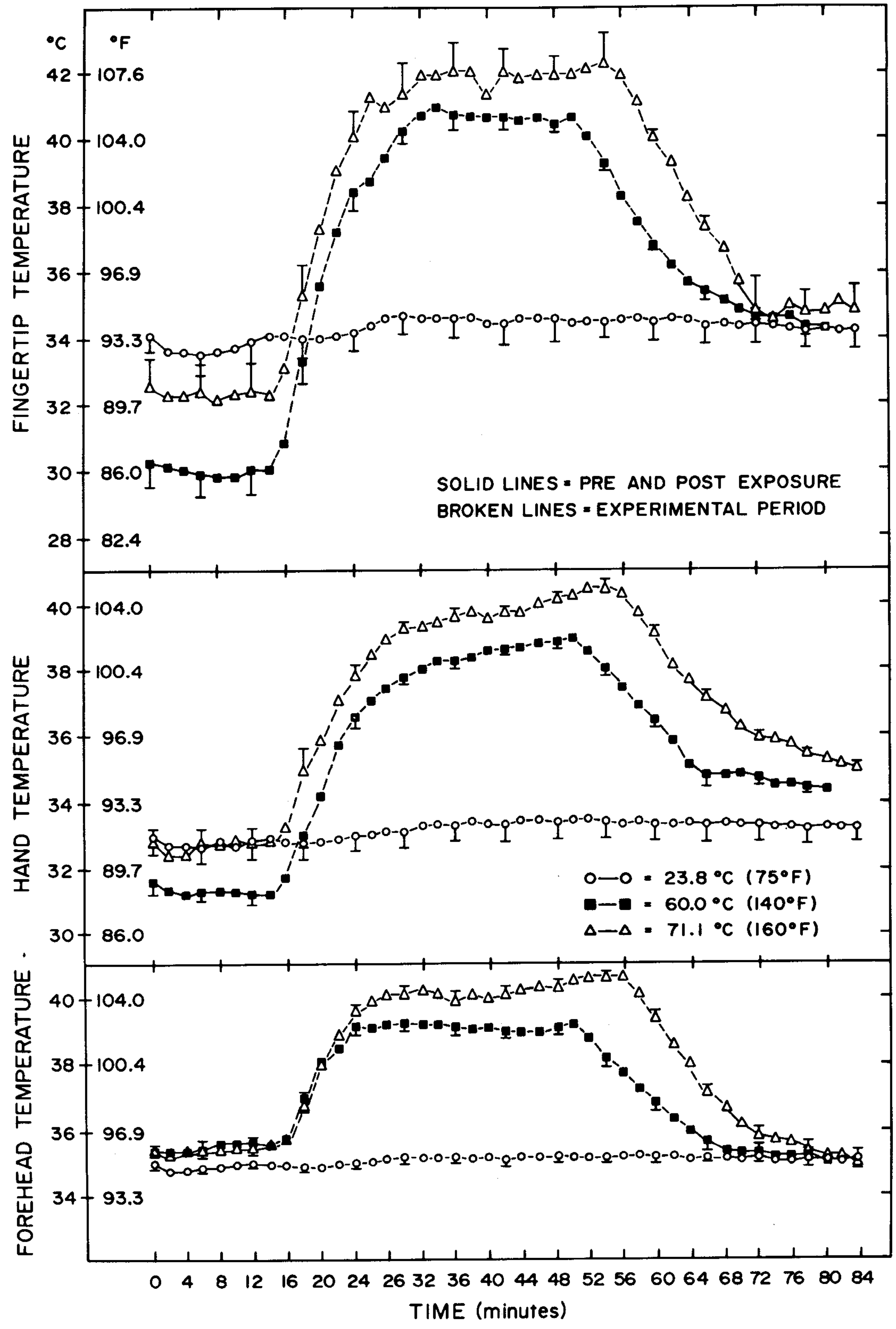


FIGURE 4—Forehead, hand and finger temperatures during exposure to 23.8, 60.0 or 71.1° C. Values are means with standard error shown at six-minute intervals.

Performance Measures. The Wilcoxon matched-pairs, signed-ranks (two-tailed) test was used to evaluate the differences between the performance during a given 5-minute interval at temperature and the 5-minute interval during the baseline period for the corresponding task combination. Thus, two tests were made for each of the major tasks (tracking [Table 1] and arithmetic [Table 2]), and three tests were made for each of the monitoring tasks (simple reaction time, discrimination reaction time, and meter monitoring [Table 3]).

It was apparent from the data that the learning asymptote had not been reached on several of the tasks prior to the beginning of the experimental run of Phase I. This is seen in the solution time measure on the arithmetic task; for both performance conditions (B and C), response times were shorter during the first subinterval at temperature than during the baseline period, and response times during the second subinterval at temperature were shorter than those for the first subinterval at temperature (Table 2). There is also a suggestion of such a trend in the monitoring tasks, but in this case, there are some reversals and the decreases are generally less pronounced (Table 3).

Phase I—This portion of the experiment was carried out in two parts, each portion involving a different sample of 10 subjects. The first sample of subjects showed significant decrements on two measures. Integrated absolute error in the horizontal dimension was greater ($P<.05$) during both the first and second subperiods at temperature under task condition A (tracking plus monitoring), and reaction times to the red light in the discrimination reaction time task were significantly longer ($P<.05$) during both subperiods at temperature under task condition A. However, several of the other time measures showed significant improvements at temperature. Response times to the green light were significantly shorter during the first subperiod at temperature under task condition C but not during the second subperiod ($P<.05$). Response times to the amber light were significantly shorter ($P<.05$) during the first subperiod at temperature under condition B but at no other time. Solution times for the arithmetic task were significantly shorter for the second subperiod at temperature under task condition B ($P=.05$), during the first subperiod for task condition C ($P=.05$) and for the second subperiod for task condition C ($P<.01$). It was the contradictory nature of the finding of improvements on several measures and decrements on others that led to the testing of the second group of 10 subjects at 60° C.

The second group of subjects showed neither decrements nor improvements as a function of exposure to the elevated temperature condition. And, when the data from both groups were combined, the overall effects of temperature were not significant; these data are summarized in Tables 1, 2, and 3, columns 1, 2, and 3.

Phase II—All of the subjects who served in Phase I were asked to serve as subjects in the Phase II experiment. The data of the 11 subjects who volunteered for this second experiment are presented in Tables 1, 2, and 3, columns 4, 5, and 6. Significant decrements were found on two of the tasks. Integrated absolute error in the horizontal dimension of the tracking task showed a significant increase ($P<.02$) during the first subperiod at temperature under task condition B, and approached significance ($P<.10$) during the second subperiod. As shown in column 6 of Table 1, the amount of error during the second subperiod was greater than the error during the first subperiod at temperature; a change in the performance of one subject produced the apparent discrepancy between the two subperiods.

Integrated error squared in the horizontal dimension showed a significant increase ($P<.05$) during both subperiods at temperature under task condition B.

The other task to show significant effects of exposure to a temperature of 71.1° C. was the arithmetic task. Under task condition C, significantly fewer problems were solved correctly during both the first ($P<.05$) and second ($P<.01$) subperiods at temperature. Under condition B, the number of problems solved was fewer than during baseline for the first subperiod at temperature ($P<.05$) but not during the second ($.10>P>.05$); however, under this task condition, the percent correct was numerically poorer during the second subperiod than during the first (column 6 versus 5, Table 2).

None of the response time measures were significantly affected by the exposure to 71.1° C.

In all cases at both temperatures, performance during the 15-minute post-experimental baseline period was statistically equivalent to that during the pre-experimental baseline period.

Phase III—The performance of the subjects in the Phase III experiment (entire period at 23.8° C.) was generally inferior to that of the subjects in Phases I and II. This is seen in Tables 1, 2, and 3, columns 7, 8, and 9. Of particular importance is the fact that the performance of the Phase III subjects was poorer than that of the Phase I and II subjects during the baseline, pre-exposure period, though not significantly so. There were no effects of time at work on any of the measures for these subjects; there were neither improvements nor decrements.

IV. Discussion.

The conditions of our study were chosen to be within the physiological tolerance limits of the subject, and the biomedical data suggest that such was the case. However, there are important reservations to be considered if any extension of these exposure times is to be contemplated. For example, the recommended physiological limit shown in Figure 5 (curve labelled "Lovelace and Gagge") indicates that at an effective temperature of 38° C. (100° F.) to 39° C. (102° F.), the tolerance time is approximately 40 minutes and the marginal physiological limit is only 90 minutes (curve labelled "Taylor"). At our higher temperature (an effective temperature of 38.4° C.

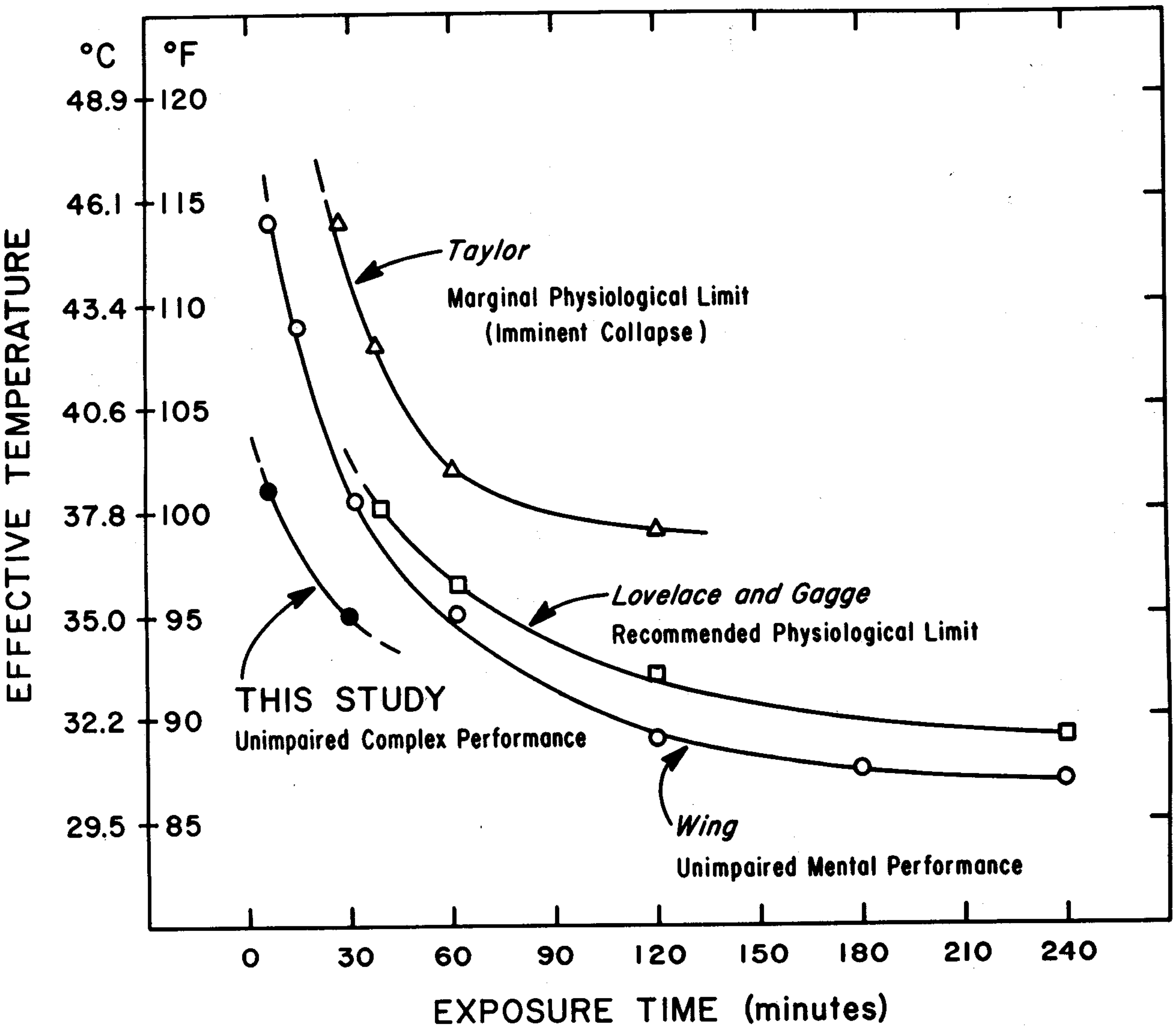


FIGURE 5—Physiological and performance limits in hot environments (modified from Wing[10]).

(101.1° F.)) both heart rate and rectal temperature were increasing rapidly at the end of the 30-minute exposure.* Although heart rate began to decrease almost immediately, rectal temperature continued to climb for about 10 minutes after the chamber temperature began to lower. Thus, it is conceivable that an additional 15–20 minutes at an effective temperature of 38.4° C. would have caused an explosive rise in either or both of these parameters with the possibility of the collapse of the subject. In addition, certain other factors became more prominent with increasing time at high temperature. These are concerned with the discomfort of handling hot, thermally conductive objects, and the mechanical effects of sweat in the eyes or on the hands. Figure 4 shows that finger temperature was 42.1° C. during exposure to 71.1° C. The pain threshold is usually considered to be about 45° C. (113° F.), and one subject in our study complained of considerable discomfort due to contact with hot metal parts of the headphone set.

At an Effective Temperature of 35° C. (which corresponds to our 60.0° C. test), Lovelace and Gagge[7] show the recommended limit of exposure to be about 90 minutes. However, it should be noted that the peak heart rate under this temperature condition was fewer than 10 beats/min. less than under the higher temperature condition at the corresponding point in time. Although rectal temperature was somewhat lower at the end of the 30-minute exposure at 60.0° C. than it was at 71.1° C., rectal temperature continued to climb in the Phase I experiment until about the time the chamber temperature had returned to normal.

The data collected with the complex performance device used in this study are probably more applicable to questions of aircrew performance during exposure to high temperature than those obtained with the tasks in most of the recent studies. First, our tasks assess functions that are intuitively involved in aircrew activities in the sense that it is difficult to see how the man could perform his aircrew duties at his normal level of competence if important decrements showed up in any of these functions. Second, and perhaps more important, the task combinations we used require time-sharing in the exercise of different psychological functions. And time-sharing seems more to characterize the role of the aircrewman in advanced aircraft. Experiments in which single tasks are performed (as is the case in most of the related research), not only do not provide a measure of this important aspect of behavior but also such tasks permit much more of an opportunity for the subject "to muster his reserves" and, thus, counteract any adverse effects of temperature by increased application to the task at hand. Further development of the rationale supporting this position can be found in a paper by Chiles, Alluisi, and Adams.[2]

The results of this study indicate that complex performance is unimpaired for 30 minutes at 60.0° C. However, this statement must be qualified in view of the fact that the first subgroup of 10 subjects tested at this temperature did show decrements on the tracking task.

For a moderate level of workload, performance was not impaired during the first 5 minutes at a temperature of 71.1° C., and, when this same task combination appeared again after 15 minutes at temperature, performance was still not impaired. However, during the second 5 minutes at temperature, both manual performance and mental performance suffered, with mental performance also showing decrements under a somewhat lighter workload during the third 5 minutes at temperature. The time figures just cited do not include the time required to raise the chamber temperature to the test level, 5 minutes and 8 minutes for the lower and higher temperature conditions respectively.

Although we interpret our data to indicate that performance is unimpaired for 5 minutes at 71.1° C., caution should be exercised in making extrapolations. The necessity for caution arises from the fact that the absence of decrements during the first 5 minutes at temperature may have been an artifact of the experimental design. Had the more complex, heavier workload condition (condition B) been presented first, decrements might very possibly have occurred immediately. Similarly, the decrements in arithmetic

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* In order to show our data on the chart constructed by Wing (Fig. 5), we converted the parameters of our conditions to effective temperatures according to the equation: ET=

$$\frac{107.5\ (\text{DB-WB}) + 62.3\ \text{WB}}{62.3 + \text{DB-WB}}$$

where DB and WB are, respectively, dry bulb and wet bulb temperatures in degrees Fahrenheit. Thus, our effective temperatures were, in degrees Centigrade (0° F.), 18.9 (66.0), 35 (95.0), and 38.4 (101.1).

performance quite possibly would also have appeared immediately had condition B or C been presented first. Putting both of these possibilities together suggests that the effects of temperature are dependent upon both the workload and the nature of the task. This inference receives support from the fact that none of the simple tasks (reaction time and meter monitoring) showed an effect of temperature.

The absence of an effect of temperature on tracking in the vertical dimension is interpreted to be the result of the fact that cross-coupling between tasks is much less likely to occur in the vertical than in the horizontal dimension. Specifically, when the subject is required to respond on one of the other tasks while tracking, he must reach with his left hand. In the case of the discrimination reaction time and the arithmetic tasks, the response involves rapid movement of his hand across the panel to points in front of the tracking control stick. Especially in making responses to these two tasks, there is a tendency for the subject to shift his body laterally. Since the subject can anchor his arm firmly on the arm rest and, thus, virtually preclude movement of his arm in the fore/aft dimension, such lateral movements of his body are much less likely to result in inadvertent inputs to the vertical dimension than to the horizontal. This implies that a major effect of temperature on manual performance is a decrease in the ability of the subject to decouple movements of the two arms.

The return of performance to the pre-exposure baseline levels during the post-exposure period is interpreted to mean two things. First, it suggests that the obtained effects were real effects of temperature and not a result of fatigue. And second, it suggests that the effects of temperature are acute and that recovery of performance is fairly rapid. The main contribution of the Phase III experiment is that it lends support to the first of these interpretations. Namely, the subjects tested for the same time period at normal temperatures (23.8° C.) showed neither increases nor decreases in their performance.

Figure 5 shows Wing's chart, slightly modified, with the results of the present study included. The curve labelled "Wing" was constructed by Wing based on his studies[11] and those of several other investigators. It shows the lowest values of temperature and exposure time at which statistically significant decrements were observed in the performance of mental tasks. Since the present study involved a task complex requiring the time-shared exercise of several psychological functions, it would be expected that our results would fall below and to the left of Wing's curve as they do. Several additional factors may have contributed to the position of our hypothesized curve. For example, our subjects were older than those used in the typical study; they were not acclimatized to heat, and they probably were not in as good physical condition as the subjects in the previous studies. All of these factors would tend to decrease the time for which unimpaired performance could be maintained.

As with any performance study conducted under laboratory conditions, there are problems in extrapolating the results to the real world. Broadly speaking, these problems lie in two categories; one is concerned with the applicability of the performance functions measured to the job the man carries out in the operational situation; the other is concerned with the procedures attendant to the testing.

With respect to the first category of problem we would argue that the task complex provided an adequate (though admittedly limited) sampling of the things the man does in the course of performing his real world work assignments, and we will not repeat arguments presented earlier in the paper in support of our position. In any event, this problem category is most critical when decrements are *not* observed.

The problems arising from the procedures used are much more involved, are, ultimately, much more a matter of experimenter judgment, and, hence, are much more subject to disagreements in interpretation. Recognizing this *caveat*, several factors combine to suggest that the times for which performance was found to be unimpaired in this study should be regarded as liberal rather than conservative with respect to generalizing to an aircraft emergency. The main reason is that the sequence of events which were to occur in this experiment was clearly understood by the subjects. And, perhaps more important, they knew (if they thought about it) that the very nature of conducting research of this sort dictates that a subject not be placed in a situation in which there is serious reason to believe that his safety or health are being compromised. They also knew that they could leave the chamber any time they felt themselves to be in any danger. Thus, it seems clear that an important factor that must be weighed (and that factor is virtually impossible to produce in the laboratory) is the implied threat of the emergency situation to the survival of the crewman and his passengers. The extent to which this additional source of stress would contribute to or compound the problem cannot be specified, but its potential for interfering with performance cannot be denied.

Counterpoised against this problem is the fact that the human operator has many times demonstrated himself to be capable of tremendous feats when the successful execution of his duties and his life and the lives of others are threatened. There is virtually no way of stating which of these two factors is more important, but the case for cautious extrapolation is clearly established.

V. Summary and Conclusions.

The research reported here involved a three-phase experiment on the effects of elevated temperatures on complex performance. In Phase I, 20 subjects were tested during a 30-minute exposure to a temperature of 60° C. (140° F.) and a vapor pressure of 13.6 mm. Hg; this corresponds to an Effective Temperature of 35° C. In Phase II, 11 of the 20 subjects used in Phase I were exposed to a temperature of 71.1° C. (160° F.) and vapor pressure of 19.9 mm. Hg (an Effective Temperature of 38.4° C.). Phase III which served as a control condition for possible fatigue effects, involved 10 subjects tested under normal temperature conditions; the temperature was 23.8° C. (75° F.) and the vapor pressure was 2.6 mm. Hg (an Effective Temperature of 18.9° C.).

The performance tasks were combined in three different ways to provide three different performance conditions varying in terms of the level and nature of the workload. Level A involved two dimensional, compensatory tracking, discrimination reaction time, simple reaction time, and meter monitoring. Level B consisted of adding a mental arithmetic task to the tasks of Level A. And Level C was the same as Level B but without the tracking task. The training of the subjects for the Phases I and III experiments involved 90 minutes of practice the afternoon before the test run—30 minutes on each of the three levels of workload. The subjects who served in Phase II were given 45 minutes of refresher training the afternoon before the Phase II test.

Data samples were taken every 2 minutes throughout the three phases on rectal temperature, heart rate, and skin temperature (recorded at the forehead, tip of the index finger, and the back of the hand). The subjects were equipped with a sweatband to preclude the possibility of easily preventable, direct visual effects of sweat.

The physiological effects of the temperature exposures were those typically found in this type of experiment.

Performance effects were observed only under the 71.1° C. condition; arithmetic scores and tracking error in the horizontal dimension both showed decrements. The tracking decrements occurred only under workload condition B; the arithmetic decrements occurred under both workload levels B and C.

The following conclusions are drawn:

1. Unimpaired performance can be maintained for a period of 5 minutes at a temperature of 71.1° C. (160° F.) and a vapor pressure of 19.9 mm. Hg. However, in a strict interpretation of the results, it must be specified that this conclusion holds only for light to moderate workloads involving psychomotor performance.

2. Decrements in psychomotor performance (tracking) and mental performance (mental arithmetic) when these functions are performed in a time-shared manner, will occur fairly quickly after exposure to 71.1° C. and a vapor pressure of 19.9 mm. Hg. Because of the specific experimental design used, this experiment does not permit ruling out the possibility that decrements with these task combinations will occur immediately upon reaching temperature.

3. Performance is unimpaired during a 30-minute exposure to a temperature of 60.0° C. (140° F.) and a vapor pressure of 13.6 mm. Hg. However, decrements were observed in tracking performance with the first subgroup of 10 subjects tested at this temperature though not with the second subgroup nor were there significant decrements when the data of the two groups were combined.

4. From the methodological point of view as regards research on environmental stress, the results of this study support the use of multiple tasks requiring the time-shared performance of different psychological functions and permitting the presentation of different levels of workload.

TABLE 1.—Tracking Performance

Measure	Workload	60.0° C.			71.1° C.			23.8° C.		
		B	1	2	B	1	2	B	1	2
Horizontal Absolute Error	A	43.26	44.78	47.38	43.34	46.64	45.23	46.76	49.04	47.44
	B	85.01	84.31	85.66	71.23	78.38*	79.01*	83.66	82.57	80.49
Horizontal Error Squared	A	9.97	9.94	12.11	8.79	10.87	9.48	10.20	12.25	8.64
	B	35.37	35.73	38.67	24.51	28.88*	29.68*	38.38	32.19	31.23
Vertical Absolute Error	A	64.96	66.60	65.06	69.81	67.88	66.07	84.34	79.34	79.02
	B	85.42	82.16	86.33	77.47	79.96	82.42	96.53	98.44	94.81
Vertical Error Squared	A	14.81	15.19	15.43	15.19	15.64	15.38	20.61	19.11	19.68
	B	30.31	27.32	32.06	22.52	25.32	27.64	33.79	37.09	31.19

*P <.05

Note: Scores are in volts with a different arbitrary scale for each measure. B=baseline; 1=first period at temperature; 2=second period at temperature.

TABLE 2.—Arithmetic Performance

	Workload	60.0° C.			71.1° C.			23.8° C.		
		B	1	2	B	1	2	B	1	2
Solution Time (Seconds)	B	5.29	4.76	4.61	4.18	4.12	3.72	5.08	4.64	4.00
	C	4.74	4.69	4.37	3.97	4.02	3.95	4.73	4.42	4.14
Percent correct	B	88.05	87.47	86.96	95.76	90.30*	89.70	87.16	93.24	89.93
	C	89.40	86.90	89.56	93.94	87.88*	87.88**	86.30	85.91	89.26

*P <.05 **P <.01

Note: B=baseline; 1=first period at temperature; 2=second period at temperature.

TABLE 3.—Monitoring Performance Mean Response Times (Seconds)

	Workload	60.0° C.			71.1° C.			23.8° C.		
		B	1	2	B	1	2	B	1	2
Red Light Reaction Time	A	.63	.61	.61	.62	.61	.59	.64	.59	.65
	B	.74	.70	.67	.75	.63	.70	.71	.79	.73
	C	.75	.70	.66	.65	.61	.57	.71	.68	.74
Red Light Movement Time	A	.47	.46	.48	.44	.49	.47	.46	.52	.49
	B	.52	.59	.56	.54	.53	.56	.60	.69	.57
	C	.56	.66	.60	.58	.53	.54	.53	.60	.67
Green Light Reaction Time	A	.65	.61	.59	.61	.56	.54	.66	.56	.59
	B	.80	.72	.77	.56	.58	.58	.66	.71	.69
	C	.68	.78	.70	.72	.59	.63	.67	.69	.62
Green Light Movement Time	A	.44	.52	.43	.43	.43	.38	.41	.46	.45
	B	.78	.59	.64	.50	.52	.52	.74	.53	.51
	C	.60	.53	54	.61	.70	.45	.54	.56	.50
Amber Light Reaction Time	A	1.09	.99	1.03	1.12	.93	1.06	1.24	1.10	1.07
	B	1.19	.97	1.42	1.22	1.03	.97	1.16	1.21	1.05
	C	1.32	1.17	1.19	1.55	1.12	1.02	1.17	1.11	1.13
Meter Detection Time	A	2.70	2.59	2.92	2.68	2.78	2.61	2.80	2.49	2.59
	B	3.28	3.29	3.41	2.89	2.97	3.15	3.02	2.97	3.00
	C	3.17	3.22	2.93	3.01	2.98	2.91	3.03	2.76	3.05

Note: B=baseline; 1=first period at temperature; 2=second period at temperature.

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