AM 68-13

THE EFFECTS OF BODY THERMAL STATE ON MANUAL PERFORMANCE

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May 1968

DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Office of Aviation Medicine

ACKNOWLEDGEMENTS

The authors express their appreciation to Dr. Thomas Adams of Michigan State University, who suggested this experiment; to Mr. Orbin Echols, of the Oklahoma Employment Security Commission for the loan of the manual performance equipment; and to Miss Betty Gatliff, of CAMI, for the technical illustrations.

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Efficient manual performance of aviation personnel concerned with aircraft repair and maintenance, and of aircrews to some extent, may depend on the interrelationships between internal and peripheral body temperature, the body thermal state. Environmental temperature is the principal stressor, and departure from a comfortable ambient temperature in which the body is thermally neutral to severe conditions of heat or cold may impair performance of aviation tasks requiring a high degree of hand and finger dexterity or motor coordination.

Physiological responses of humans to whole body and peripheral changes in ambient conditions have been studied extensively by a wide variety of methods, depending on the type of information desired.[4,8,13,18,30] Several investigators have related whole body temperature to physiological responses of hands and fingers to describe the changes in manual performance.[3,10,15,24] Emphasis has been on cold exposure, and results were often complicated by protective clothing or by environmental conditions which did not permit adequate and separate assessment of internal body temperature and skin temperature.

This experiment proposes to relate manual performance to the thermal state of semi-nude men exposed to cold, thermally neutral, and hot environments. Performance is evaluated in terms of changes in the body thermal state, which include the central thermal state, as measured by internal body temperature, and the peripheral state, as reflected by average skin temperature, hand temperature, and cold-induced vasodilatation of the finger.

I. METHODS

Thirty-six young men, chosen at random, were exposed in pairs for 2 hours to environmental temperatures of 10°C (50°F)±1°, 26.7°C (80°F) ±1°, or 46°C (115°F)±1°. Relative humidities were 50±2% at 10° and 26.7°C, and 40±3% at 46°C. Physical characteristics are shown in Table I. Experiments at these conditions were conducted in the early morning, when rectal temperature (T_r) was lowest, and in the early afternoon when T_r was relatively high[17,27]. T_r was determined by a bridge and a calibrated thermistor probe inserted 10 cm into the rectum, heart rate (HR) by electrocardiogram leads, and respiratory rate (RR) with a mercury strain gauge plethysmograph. All three were recorded on a six-channel Grass recorder. Measurements of skin temperatures were made with a Stoll-Hardy radiometer (Model HL4)[25] calibrated with a Leslie Cube at each of the three ambient temperatures. Average skin temperature (T_s) was calculated from the seven-point system of Hardy and DuBois[14], and average body temperature (T_b) from the equation: $T_b=0.65\ T_r\ +0.35$

TABLE I. Physical characteristics of men exposed to three environmental conditions and at two times of day

		Height, cm	*Weight, kg*	*Age, Yr.*
Cold 10°C	a.m.	178.9 (173.4–182.9)	77.12 (62.79–87.26)	22 (19–25)
	p.m.	173.3 (167.0–183.5)	67.43 (54.93–78.12)	22 (21–27)
Neutral 26.7°C	a.m.	181.4 (177.8–184.8)	75.70 (67.50–92.18)	22 (18–29)
	p.m.	175.2 (169.5–180.3)	74.27 (63.21–97.93)	22 (21–24)
Hot 46°C	a.m.	183.2 (175.9–188.6)	82.62 (71.90–102.75)	23 (19–29)
	p.m.	180.7 (174.0–189.2)	79.04 (68.99–86.09)	22 (19–24)
TOTALS (N=36)		178.8 (167.0–189.2)	76.03 (54.93–102.75)	22 (18–29)

Values are means; ranges are shown in parentheses.

T_s developed by Burton[5]. Cold-induced vasodilatation (CIVD)[20] consisted of measuring changes in finger temperature after immersing the right index finger for 20 minutes into a mechanically stirred bath to a level midway between the distal and middle joints. Temperature was monitored by a No. 40 gauge copper-constantan thermocouple attached to the tip of the finger with a single layer of plastic tape, and was recorded by a Varian recorder.

Hand and finger dexterity and motor coordination were determined from parts of the General Aptitude Test Battery, developed by the United States Department of Labor[12]. Figure 1 shows the peg board for the two-part hand dexterity test. The first part (Figure 1A) consisted of placing pegs from the holes at the top of the board to corresponding holes in the lower part of the board as quickly as possible in 15 seconds. In the second part of the test (Figure 1B) the

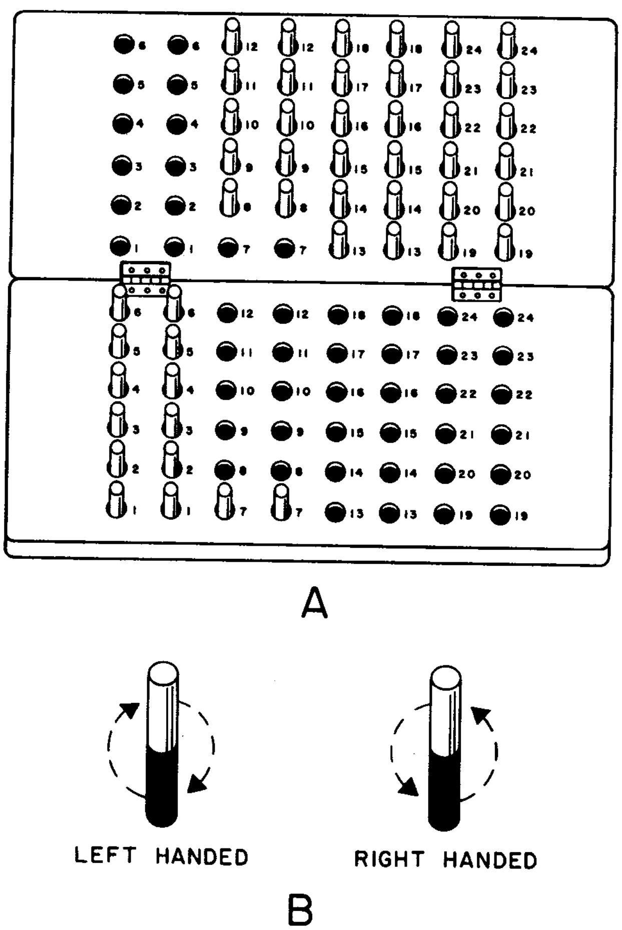

FIGURE 1. Hand dexterity test. (A) Pegboard and pegs for placing test. (B) Correct direction for turning peg with one hand in peg turning test.

subject picked up a peg, turned it over with one hand, and put it back into the same hole. A practice trial was followed by three test trials of 30 seconds each. Scores were the total number of pegs placed or turned for the three test trials.

The finger dexterity test is shown in Figure 2, and was also in two parts. It consisted of a board with two sets of holes, the upper set containing metal rivets (Figure 2A). A metal rod strung with washers was attached to one side of the board. The subject assembled the rivets and washers, then inserted as many as possible into the corresponding holes at the lower part of the board within 90 seconds (Figure 2B). The second part consisted of disassembling and replacing as many washers and rivets as possible in 60 seconds. One practice trial was allowed before the test trial. Scores were the number of rivets and washers successfully assembled or disassembled within the given time periods. The motor coordination test (Figure 2C) consisted of making three lines in a square as rapidly as possible. Two 10-second practice trials were followed by a single test trial for 60 seconds and scores were the total number of squares containing the lines. A schedule of events during an exposure is given in Table II.

TABLE II. Schedule of Events

Time, Min.	
0–30	Hookup, sit quietly; T_r, T_s, HR, RR at 0, 15, and 30 min.
31–75	CIVD measurements; T_r, T_s, HR, RR at 45, 60, and 75 min.
76–105	Hand, finger dexterity, and motor coordination tests; T_r, T_s, HR, RR at 90 and 105 min.
106–120	Sit quietly; T_r, T_s, HR, RR at 120 min. End exposure.

Each subject, wearing only shorts, was instrumented in an air conditioned dressing room maintained at 25°C and adjacent to the climatic chamber. The men were weighed prior to exposure, and those scheduled for 46°C were weighed again after exposure to determine sweat output.

II. RESULTS

Figure 3 shows changes in RR, HR, T_r, T_b, and T_s through the time for the three ambient conditions studied. An analysis of variance[28] comparing neutral conditions with cold showed that T_r, T_s, T_b, and HR were significantly different in the cold and during the morning exposure, but that T_r did not vary through time. RR was lower in the morning than in the afternoon, but was not influenced by differences in chamber temperature or through time. Comparisons between the neutral and hot environment indicated significant increases in all the parameters due to chamber temperatures. T_s showed no direct effects from morning to afternoon, or through time, and, as in the cold, there was no change in RR through time. Changes in T_b through time in the cold were largely due to the significant decrease in T_s, as T_r did not change with time, whereas those in the heat were influenced more by the increasing T_r, as T_s did not change significantly through time. The interaction between chamber temperature and time also supports this result.

the skin by convection for subsequent dissipation by evaporation of sweat at the surface.

Mean heat debts calculated for morning and afternoon exposures, were 102 and 131 kcal in the cold, and 23 and 13 kcal at the neutral conditions respectively, whereas, subjects exposed to heat showed mean heat gains of 26 and 48 kcal in the morning and afternoon respectively.

The curves in Figure 4 show changes in temperature of the palm of the hand for the three environments. Mean hand temperature in the heat rose 1.6°C in the morning and 2.6°C in the afternoon, whereas those in the cold fell 7.9°C in the morning and 10°C in the afternoon. Temperatures at neutral conditions remained fairly stable. Tests for significant differences between means of paired data[28], showed that the afternoon

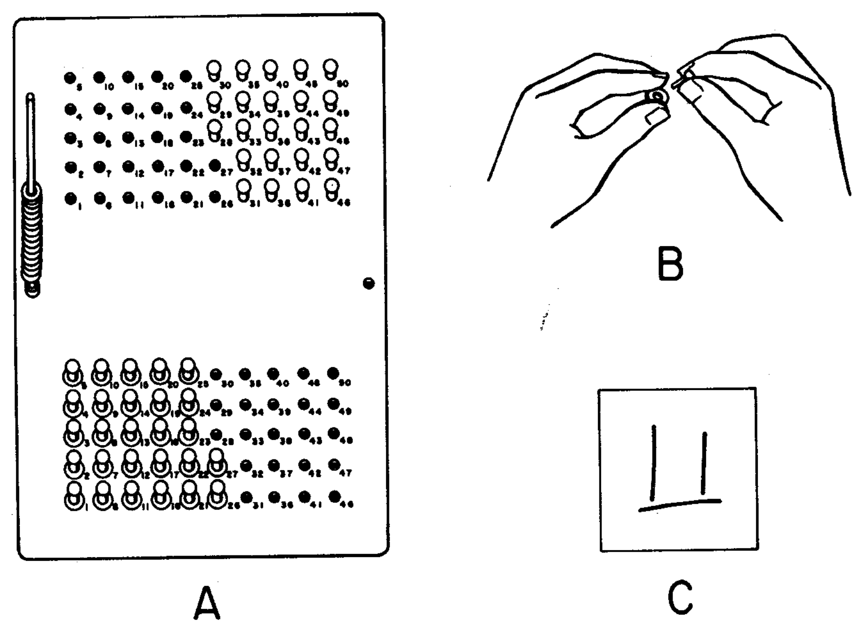

FIGURE 2. (A) Board with rivets and washers for finger dexterity tests. Rod containing washers is attached to the right side of the board for left-handed test subjects. (B) Correct method of assembling a rivet and washer for a right-handed subject. (C) Three-line configuration for motor coordination test.

Further interactions of chamber temperature with exposure time and with time of day (AM-PM) showed that the apparent increase in heart rate at 10°C was probably due to the low morning rates observed at 26.7°C, whereas increases at 46°C were caused more by the higher chamber temperature rather than time of day. Heart rate also increased with exposure time in the heat, promoting transfer of deep body heat to

values in the cold were significantly lower than morning values from 30 minutes through 60 minutes. Reasons for this temperature inversion are not clear. Temperatures at 75 and 90 minutes were not significantly different probably because of the large variability caused by excessive movement during the dexterity tests.

Results of CIVD (Figure 5) were analyzed for six combinations of rectal temperature and

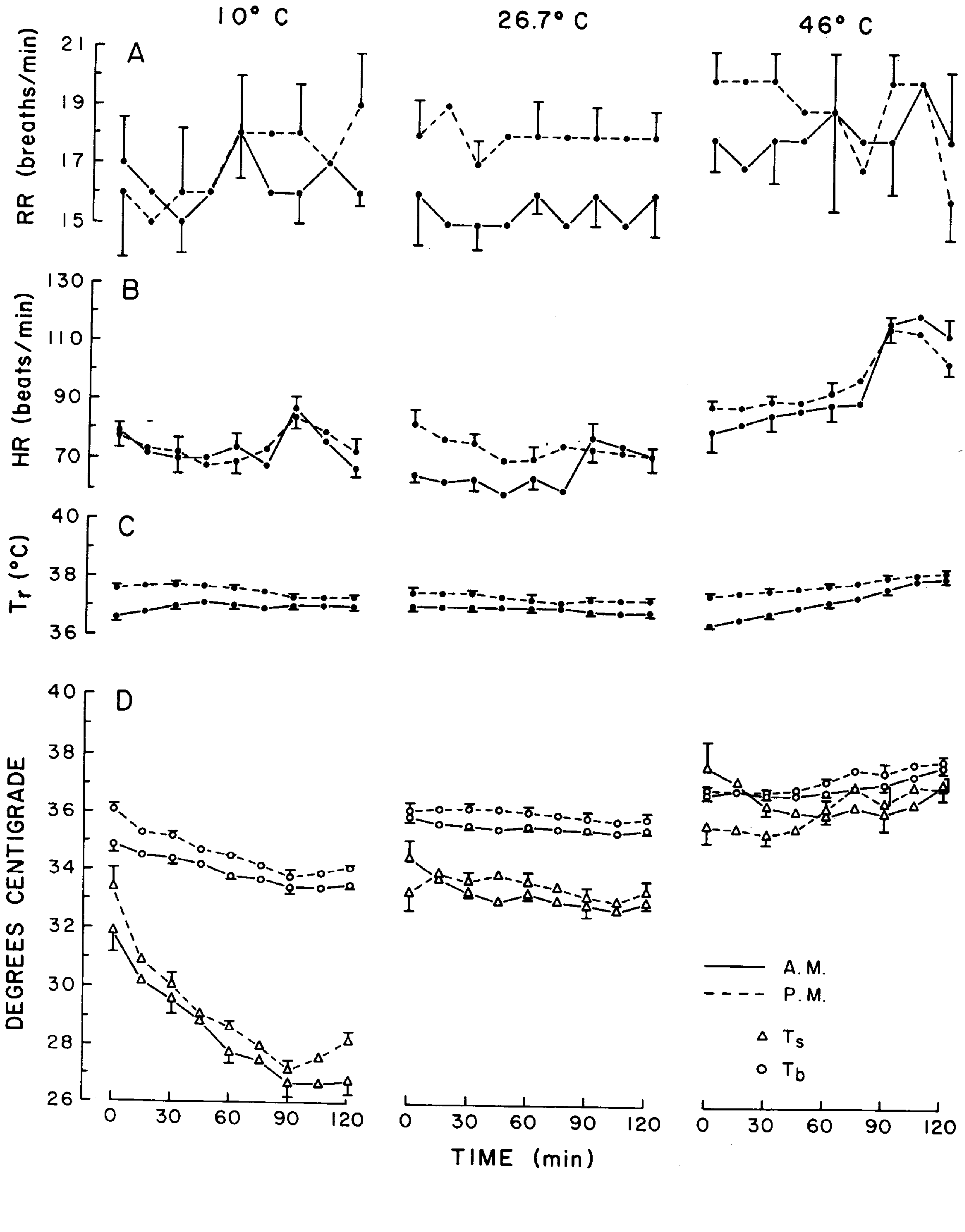

FIGURE 3. Physiological responses to ambient temperatures of 10°C, 26.7°C, and 46°C. n=6.

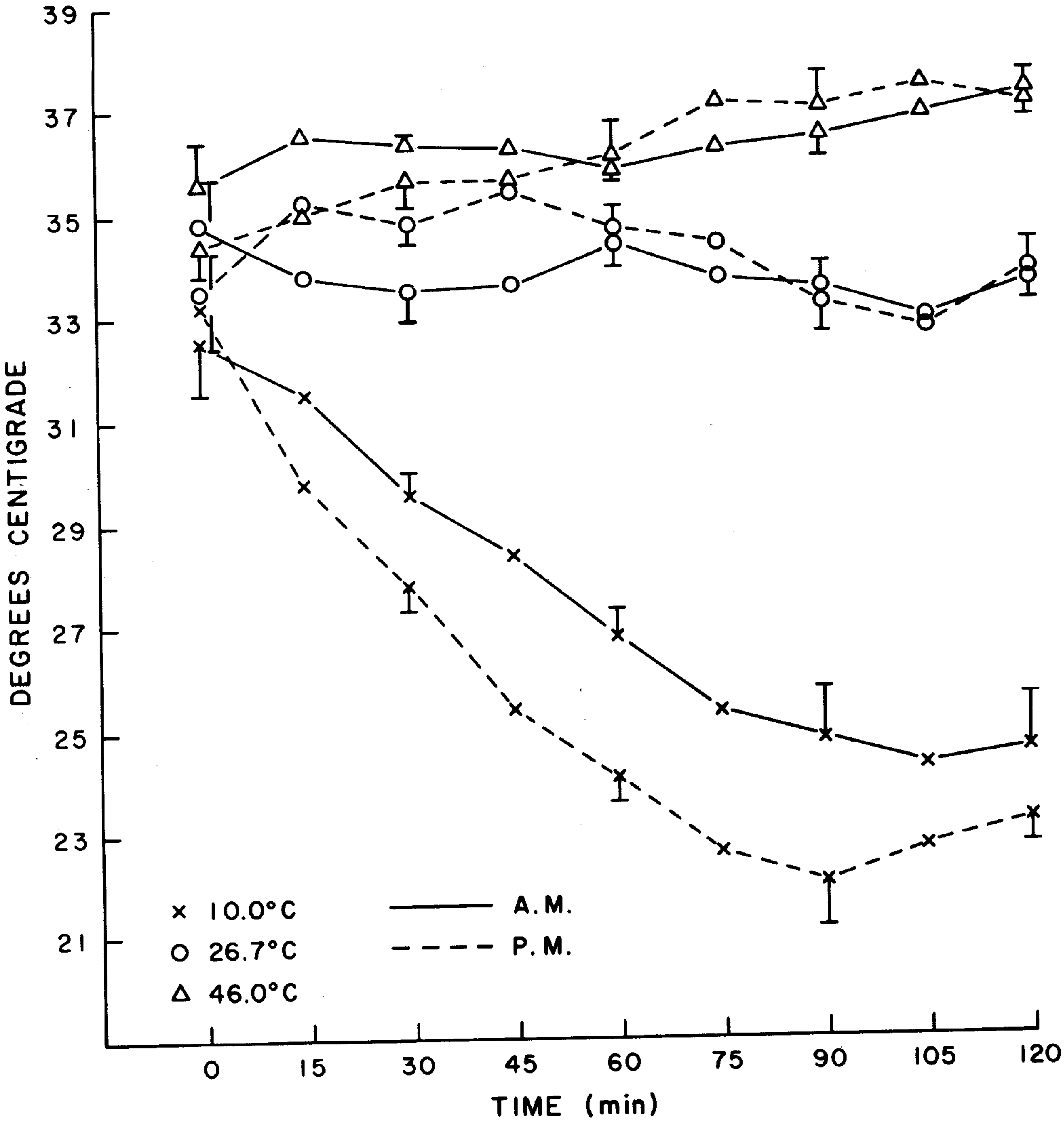

FIGURE 4. Hand temperatures (palm) at ambient temperatures of 10°C, 26.7°C, and 46°C. n=6.

average skin temperature, by comparing the means in a paired "t" test[28].

The most striking feature of subjects in the cold was the absence of spontaneous vasodilatation. Initial finger temperatures (temperatures in air prior to immersion, Figure 5A) and cooling rates (rate of cooling for the first 3 minutes of immersion, Figure 5B) were significantly higher at the low rectal temperatures. Initial finger temperatures in the heat were higher than those at the neutral conditions, which in turn were higher than those in the cold. Cooling rates at the neutral conditions were also higher than those in the cold, but rates in the heat were higher than at neutral only for the low rectal temperatures. Rewarming rates (Figure 5D) and rewarming temperatures (Figure 5E) were not different at any given level of thermal state, but those in the heat were significantly higher than those at the neutral conditions.

At neutral skin temperatures, cycling times (Figure 5C) were significantly shorter at the higher rectal temperatures, whereas at high skin temperatures, cycling times were shorter than those at neutral conditions only when levels of rectal temperature were the same. One subject at the neutral condition and three subjects in the heat failed to show the vasodilatation response.

Converted scores of the manual performance tests, together with the standard errors are shown in Table III. These scores were analyzed by a test of significant differences between means of paired data for all possible combinations of T_r and T_s.

Placing the pegs was independent of body thermal state, but the highest scores for turning the pegs and for assembling the washers and rivets were found at neutral skin temperatures when rectal temperatures were high. Scores for disassembling were also higher when the body was warm, but were less dependent on internal body temperature. Motor coordination scores were statistically higher in the heat, but subjects in the cold performed better than those with neutral T_s and low T_r.

Values of mean sweat rate were 12.04 g/kg during the morning exposures, and 15.38 g/kg during the afternoon, but there was no significant difference between the two exposures at or below the 5% level of probability ($p<.10>.05$).

III. DISCUSSION

The data of this experiment indicate that the degree of proficiency of manual performance is governed by the interrelationships among the central thermal state, the peripheral thermal state, and the complexity of the task.

The hand placing tests, requiring only coarse movements of the hands and arms, were independent of thermal state, but hand turning scores, which involved more discreet use of the hand and fingers, were improved only when T_s and T_r were maintained at high levels. Assembling the washers and rivets, which required fine coordination of the fingers, was best performed in a thermally neutral environment. Profuse sweating at 46°C, and the frequent bouts of shivering observed at 10°C were possible factors contributing to impaired kinesthetic sensitivity in these environments. Disassembling the washers and rivets was less exacting and although scores were somewhat better at the neutral and hot conditions they showed little difference from the thermal state in the cold. Bartlett and Gronow[3], studied dexterity in clothed men at ambient temperatures of −10°C and also found that screwing and unscrewing bolts into a nut was more difficult than a peg placing test.

Scores of the motor coordination test were significantly higher in the heat than in neutral or cold conditions, but subjects in the cold scored higher than those with neutral skin temperature and low T_r. Fox and his coworkers[9] reported that when body temperature was raised to 38.5°C,

TABLE III. Converted Mean Scores of Performance Tests
n=6

Ambient Temperature		*Hand Dexterity*		*Finger Dexterity*		*Motor Coordination*
		Place	*Turn*	*Assemble*	*Disassemble*	
10°C	AM	26±5.6	57±2.8	29±5.0	57±2.5	113±3.7
	PM	16±4.1	54±3.7	31±5.5	52±2.7	115±9.0
26.7°C	AM	23±6.5	64±2.0	41±6.1	61±1.5	104±6.0
	PM	28±3.6	77±2.6	51±3.5	65±2.3	119±3.2
46°C	AM	20±5.9	74±1.6	28±6.2	60±1.6	128±6.4
	PM	27±5.0	82±3.8	45±4.5	65±2.4	132±5.4

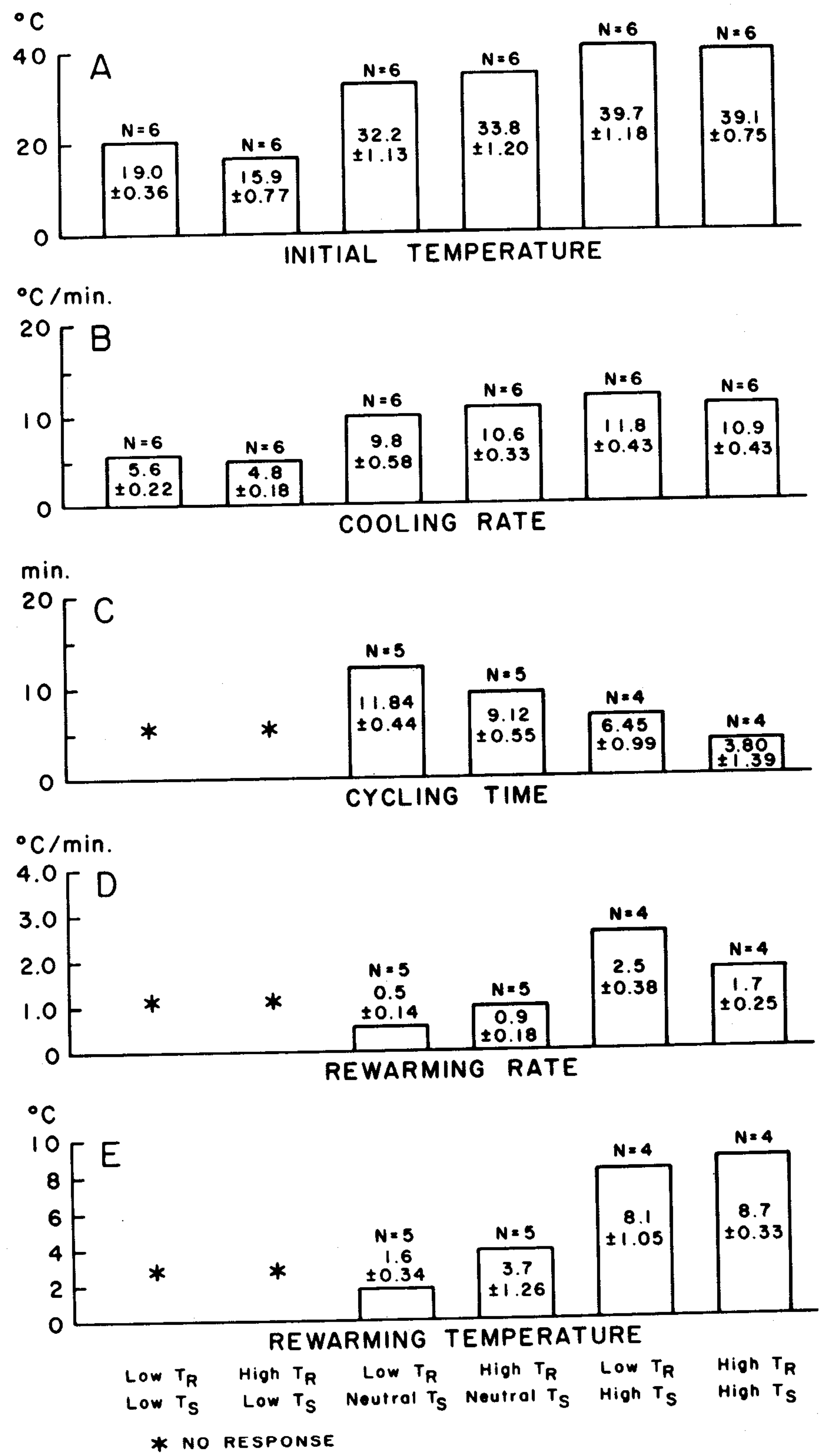

FIGURE 5. Thermal responses of the right index finger immersed in stirred ice water for 20 min. for six body thermal states.

both speed and accuracy in arithmetic problems deteriorated, but that vigilance was improved. Wing[29], using effective temperature (ET) to define upper thermal tolerance limits of mental performance for a variety of tasks, showed that the physiological limits were always higher than those for mental performance, and that impairment occurred at an ET of 31.7°C for a 2-hour exposure, a value somewhat lower than the ET of 35°C, calculated for the hot condition of this study. Impairment here may be due to the nature of the test, which measures the ability to coordinate eyes and hands or fingers rapidly and accurately, rather than the degree of cortical activity. Gaydos[11] exposed men to 7.2°C but found no impairment of tying knots or stringing blocks as long as hand skin temperature was maintained at 27°C, while Clark and Cohen[7] thought that decrements in performance accompanying cold exposure increased as the rate of hand cooling decreased. The consistently poor showing of finger dexterity in the men exposed to 10°C was probably not caused by any loss of tactile discrimination of the fingers, as Morton and Provins[22,23] exposed the index finger to cold air or to cold water, and found no deterioration above finger temperatures of 8°C, or about 7 to 10 degrees below the mean initial finger temperatures measured here (Figure 5A). LeBlanc[19] and Hunter[16] independently reported impairment of finger dexterity in the cold, and thought it to be due to increased viscosity in the synovial fluid of the joints of the fingers and hand. There may have been some stiffening of the joints of the fingers of subjects at 10°C, but comparisons were difficult because the methods of cooling differed from those in the literature.

The lack of CIVD response in all subjects exposed to 10°C and in the four exposed to the higher ambient conditions may have different causes. Blaisdell[4] studied men for several hours and found induced vasodilatation to occur, even when the body was chilled at ambient temperatures down to 12°C, although cycling time increased at the lower temperatures, and Keatinge[18] found that finger vasodilatation in chilled men may be delayed as long as an hour and a half. Thus, the subjects here might have vasodilated if exposure time had been extended beyond 20 minutes. Absence or impairment of the CIVD response in subjects in a comfortable or warm thermal state may be attributed to effects other than temperature or individual variability. Bader and Mead[2] showed that with subjects adequately warm, both hand and finger cooling produced no changes in blood flow in the cooled finger as compared to a control finger except when the subjects were startled by a loud noise or took a deep breath. Then vasoconstriction, accompanied by reduced blood flow and finger cooling occurred in both the cooled and controlled digits. Adams and Smith[1], Meehan[21], and Teichner[26] found that an emotional disturbance such as anxiety elicited vasoconstriction in the finger, resulting in delayed cycling time or absence of induced vasodilatation. Possibly apprehension of the unusual test situation was a contributing factor here, but as none of the subjects were evaluated psychologically, speculation only can be made on this point.

The higher hand and finger temperatures of subjects at 10°C (Figure 4) which occurred at the lower T_r, may have been induced by excessive shivering. Carlson[6] found that the adequate stimulus for shivering depended in part on the central thermal state, and that lowered internal body temperature encouraged the tendency to shiver. Morning T_r rose 0.5°C during the initial 45 minutes in the resting men, indicating either a higher degree of shivering or more efficient heat conservation over that of the afternoon exposure (Figure 3C). Possibly both muscle and cutaneous blood flow were increased enough to raise the hand temperature.

The physiological and manual performance data suggest that decrements in dexterity, particularly those involving kinesthetic sensitivity, depend largely on maintaining the integrity of the shell temperature, with the core temperature in a secondary role.

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APPENDIX A

Occupational Aptitude Pattern Scores of Experienced Workers For Ten Aviation-Related Occupations*

Occupational Aptitude Pattern		*Cutting Scores*	
OAP No.	*Description*	*Manual Dexterity*	*Finger Dexterity*
24	Aircraft and Engine Mechanic	—	80
20	Aircraft Mechanic, Armament	85	—
22	Aircraft Mechanic, Heat and Vent	80	75
22	Aircraft Mechanic, Plumbing and Hydraulics	80	75
22	Aircraft Mechanic, Rigging and Controls	80	75
22	Assembler, Aircraft Power Plant	80	75
22	Assembler, Aircraft Structures and Surfaces	80	75
20	Electrician, Airplane	85	—
22	Instrument Panel Assembler	80	75
32	Parachute Maker (Eight categories)	80	80

*Extracted from: General Aptitude Test Battery, B–1002, Section II: Norms—Occupational Aptitude Pattern Structure, Bureau of Employment Security, U.S. Dept. of Labor, Washington, D.C., 1966.