THE PHYSIOLOGICAL AND PERFORMANCE RESPONSES
WITH A WATER COOLED HOOD IN A HEAT STRESS ENVIRONMENT
WHILE DOING CREATIVE MENTAL WORK

by 45

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B.Sc. (Electrical), Punjabi University, India, 1966

A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Industrial Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1969

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ACKNOWLEDGEMENTS

The author wishes to acknowledge the aid of the faculty and staff members of the Institute of Environmental Research in the development of this thesis. He is particularly indebted to his major professor, Dr. Stephan Konz, who provided continual guidance and advice. Last, but not least, he wants to express his gratitude to Mrs. Sharon Morrisey for her nice typing in a short period of time.

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INTRODUCTION

Man not only has the capacity of performing complex psychomotor tasks that far exceed anything yet demonstrated by other kinds of animals, but he is also distinguished from all other organisms in having the most sensitive and efficient body-temperature mechanism (Hendler, 1963). It is man's brain, of course, that is largely responsible for his performance capability. In order to function properly, the brain requires an environment that is maintained in a state of dynamic equilibrium. An essential part of this environment, which must remain stable, is thermal. While the temperature of many of the more peripheral parts of the body can vary considerably from time to time and place to place, those of the inner "core", and especially that of the brain, are kept within narrow limits by a host of complex mechanisms. Small changes of the brain temperature, amounting to a few degrees in either direction, if not compensated for, produce profound physiological alterations (rectal, body temperatures, sweat loss, etc.) that result in a rapid deterioration of performance capability.

When the environment is too hot as compared to non-stressful conditions and it becomes impracticable or uneconomical to cool the environment, heat normally is either stored in the body or is removed from the body by radiation, convection and evaporation of sweat. This study used a fourth method of removal, conduction; specifically, cool water in a hood conducted heat away from the blood. The purpose of this investigation was to study man's physiological and mental responses while being cooled with the hood.

LITERATURE REVIEW

The literature survey is in the following order: heat stress environments, their effect on mental responses, their effect on physiological responses, and reduction of heat stress environments.

Heat Stress Environments:

The heat stress of any given working condition is defined by Leithead and Lind (1964) as the combination of all those factors which result in heat gain to the body or which prevent the body's heat mechanism from working efficiently. Thus, it is necessary to consider both climatic (air temperature, humidity and air movement) and non-climatic (radiant heat and clothing) factors, when describing a heat stress situation. The physiological responses in a stress environment can be compared to the basal physiological responses in a non-stressful environment to obtain an indication of thermoregulatory strain.

When, in the heat stress environment the heat storage exceeds the range allowed by the system, the thermoregulatory mechanisms are not only disrupted but disorganized too. Leithead and Lind state that the range of complete functional efficiency of the system is exceeded when core temperature is in excess of 103 F. But, the control of the thermoregulatory mechanisms does not depend on core temperature alone. Leithead and Lind state that, in order to maintain thermal equilibrium, the skin temperature must be lower than the core temperature. They say that, if this relationship is maintained, then the body is capable of transferring adequate quantities of heat from the core to the skin for dissipation to the environment.

The physiological responses that can be easily and conveniently measured, and have been used by different investigators, to assess the strain imposed on man when he is exposed to a heat stress situation are: rectal and skin temperatures, weight loss and heart rate.

Mental Responses:

A host of studies have been undertaken to study the effect of heat stress environments upon mental performance. Barcroft (1938) states that under heat stress "it is not the body of man that gives but the mind".

Mackworth (1946, 1950), Pepler (1958), Fine et al. (1960), Givoni and Rim (1962) and others investigated the effect of heat stress upon mental performance. Most of them found a decrease in mental performance with an increase of environmental temperature. Wing (1965), after reviewing the results of fourteen experiments by different investigators, concluded that mental performance deteriorates well before the physiological limits are reached. He found an inverse, exponential relationship (Fig. 1) between exposure time and the lowest temperature yielding significant impairment. He compared this curve on mental performance with the recommended physiological limits of Lovelace and Gagge (1946) and the marginal physiological limits of Taylor (1948). As is seen from Fig. 1, Wing's performance curve lies below the recommended physiological tolerance curve and the marginal physiolo-

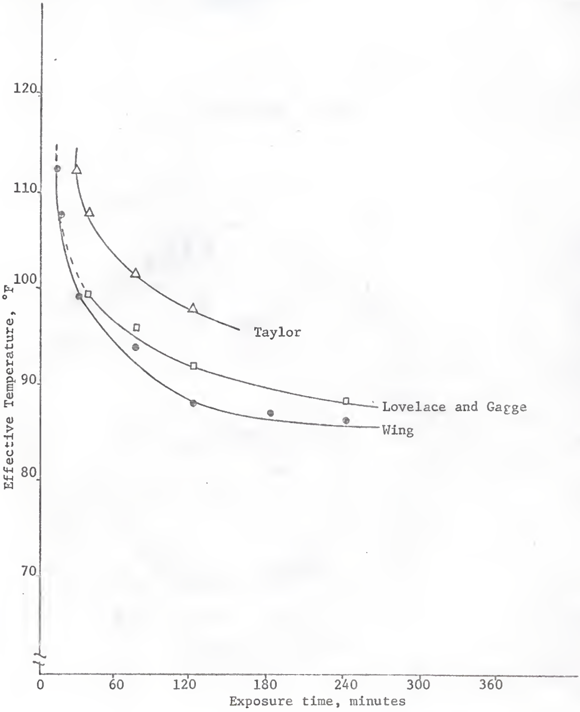

Fig. 1. Comparison of the proposed thermal tolerance limit for unimpaired mental performance (Wing) with both the recommended physiological limit (Lovelace and Gagge) and the marginal physiological limit (Taylor).

gical curve.

Physiological Responses:

Brouha (1960) states that physiological responses of man in a heat stress environment depend upon a number of factors: water and salt content of the body, state of health and nutrition, degree of physical fitness, heat of acclimatization and heat load. The physiological responses are altered in various ways. With an increase in environmental temperature, body and skin temperature increase and this, in turn, affects the circulatory activity and the availability of oxygen from the lungs ultimately to the muscles. The circulatory system is a closed tubular system with a relatively constant volume of blood (Grollman, 1964). Grollman states that, in the circulation of this constant volume, the following factors are of fundamental importance: cardiac output (rate and volume), blood pressure and peripheral resistance. The volume-capacity ratio of the fluid in a closed circulatory system cannot exceed unity and, if it is less than unity, some part of the system may receive less fluid supply than is necessary for the functional state of the tissue. In the circulatory system, the pulsating heart outflow is about 120 mm Hg. systolic pressure which is necessary to overcome peripheral resistance. This amount of blood must equal the inflow to the heart to assure a continuous flow in the system. This balance is important because in the elevated environmental temperatures one of the first corrective actions initiated by the heat regulating centers to meet an imbalance is dilation of skin blood vessels by means of sympathetic nerve impulses. Any extensive dilation of the skin blood vessels may threaten the volume-capacity ratio of the circulating system. The threat may be overcome only if some part of the system is closed or additional liquid added. Both may occur as blood vessels of the viscera may be constricted and fluid may be shifted from one fluid compartment to another. But the former cannot be continued very long without threat to the viscera, while the latter takes time and is limited in extent. Should the peripheral resistance decrease as a result of peripheral or skin vasodilation, cardiac output is altered to maintain the necessary pressure in the system by changing the heart rate as well as the stroke volume to maintain the flow through the system.

Williams et al., (1962) report that cardiac output in the heat does not change from the non-heat condition. Selle (1952) states that, in severe heat, blood flow through skin capillaries may be increased as much as 30 fold; therefore it appears that the heart must increase either stroke volume or heart rate. But stroke volume may be reduced in the heat, so the heart rate may be increased.

Selle (1952) states that, under hot conditions, sweat rate increases; the liquid is derived from the extracellular fluid which includes both blood plasma and interstitial fluid. With increased sweating the intracellular fluid moves into the extracellular compartment (to maintain osmotic pressure) which may result in dehydration unless fluid (and salt) intake maintains normal water balance.

Reduction of the Heat Stress Environments

One approach to individual body cooling is a ventilated suit (Crockford et al., 1961 and Veghte, 1965) in which cool air is blown over the man to improve the evaporation of sweat. Ventilated suits cool man by evaporation and convection and use the rapid expansion of compressed air, discharged through a multipoint distribution system inside a loose fitting garment. A air ventilating suit prevents serious heat storage but usually with a sweat loss of significant magnitude which may cause consequent dehydration.

Veghte (1965) reports that a water cooled suit proved superior to all of the air ventilating suits. Webb and Annis (1967) reported that with a water cooled system their subjects showed no evidence of heat stress.

Cooling suits, such as the ones described above may be used in a hot-humid environment but their main limitations are that they encase the entire torso and/or all four limbs, which obviously restricts mobility and requires more effort and power requirements in some conditions. These limitations have led to another approach to removing heat -- a water cooled hood.

Effect of Localized Cooling: Todd (1944) observed that during immersion of a hand in water near the freezing point the rise of blood pressure diminished if the same hand was immersed in cold water on successive days while the subjects were at room temperature.

Belding (1949) reported that Nova Scotia fishermen, whose hands had been continually exposed to cold, produced no increase of blood pressure during immersion of their hands in cold water. Yoshimura and Iida (1952) have shown that immersion of both legs and feet in ice water for 15 to 30 minutes daily resulted, after one month, in a diminution of pain during cooling. Glasor and Whittow (1957) studied the physiological effect of immersing one hand in 39.2 F water for 60 second intervals for a number of days on six Asians and two Europeans living in Singapore. They found that the rise in blood pressure and heart rate was significantly diminished and the pain of cooling was abolished with time. They state that this localized acclimatization persisted for intervals of up to 24 hours. These findings suggest that physiological adjustments to localized cooling can be induced. A possible explanation is a lower triggering threshold for vasoconstriction (which increases peripheral circulatory resistance) obtained through acclimatization.

Investigators interested in man's physiological behavior in hot conditions also have studied the effects of localized cooling and of lowering internal temperature artificially. Winslow and Herrington (1949) reported "vasomotor phenomena" that occurred when an ice bag, covering about 60 square centimeters (9.3 square inches), was applied for 15 minutes to the nape of the neck of the subjects that were in what they considered to be a stage of vasodilation (chest temperature 96 F). They concluded that localized chilling of the neck had a prolonged progressive influence on the skin temperature of the tip of the index finger of the right hand. They described the effect of the ice bag in lowering skin temperatures to be similar to those effects produced by local "cold" radiation or drafts.

Benzinger (1959) influenced cutaneous and "internal body" temperatures separately. Benzinger's "internal body" temperature was influenced upwards by exercise and downwards by the subjects repeatedly eating an ice water emulsion. Cutaneous temperature was influenced by varying ambient temperature and humidity. Benzinger found that by lowering "internal" temperature he depressed sudomotor activity. He came to the conclusion that it is the combination of two human sensory systems for temperature, and two complete and independent mechanisms of heat regulation working in concert, that produce precision temperature control. These mechanisms are the sensory-receptor organs in the skin and in the hypothalamus that have dual control on the effector organs of sudomotor activity in the skin. Guyton (1966) states that stable operation of a control system requires that the receptors exciting the control system detect the factor that is being controlled. In this instance the factor that is being controlled is the internal body temperature.

<u>Where Should the Conductive Liquid Touch the Body:</u> Guyton (1966) states that 15% of the total blood flows through the brain, 49% through the kidneys and liver, 15% inactive muscles, and 21% through the skin,

heart, bone, glands and other tissues. Further it was analyzed that the head is the external location close to a large constant blood flow. Froese and Burton (1957) reported that the tissue insulation of the head was constant over a wide range of temperature. According to Edwards and Burton (1960), the higher temperature areas on the surface of the head were the forehead, scalp, and the neck. They found that, at a 32 F environmental temperature, forehead temperature was as high as 74 - 79 F and the scalp 82 - 86 F.

Winston and Herrington (1949) and Webb (1966), while studying man's physiological responses in heat altered environments, concluded that the head has the highest skin temperature and thus the largest temperature differential. Burris (1965) described the head as the area of highest insensible sweat rate on the body.

Morales and Konz (1968) designed a water cooled hood to cool man's blood and thereby lower the internal temperature. It consisted of a canvas hood with rubber tubes, through which cold water passed, glued on the interior surface. They exposed their subjects to both non-stressful (ET of 71 F) and heat stress conditions (ET of 93 F). The task consisted of pedalling a bicycle ergometer at a work output rate of 0.1 hp at 40 rpm. They found that sweat loss was reduced, indicating less circulatory strain. In those persons wearing the hood a lowered heart rate was observed. These persons had a prolonged exposure time to heat stress conditions and the rectal, limb and head temperatures all were lower than in those individuals without the hood.

It appears that a cooling hood is one promising approach to protect men working in heat stress (where it is impossible or uneconomical to cool the environment). It requires less power than other systems and mobility is good since arms, legs and torso are not encased.

PROBLEM

On the basis of the literature search, the following conclusions are made:

1. There is no published data of any experiment investigating the effect of a heat stress environment upon mental performance using a water cooled garment of any kind.
2. Different criteria, namely heart rate, rectal temperature, skin temperature, and oxygen consumption have been used by different investigators to determine indices of physiological and mental strain. No experiment is reported which used standard deviation of instantaneous heart rate as an index of mental strain (Kalsbeek and Ettema, 1965) in the heat.

Taking into consideration the above points, it seemed appropriate to investigate the effect of a heat stress environment upon physiological and performance responses with a water cooled hood. Criteria measured were: productivity, sweat loss, rectal, limb and head temperatures, heart rate and standard deviation of the instantaneous heart rate.

METHOD

Task: The task required creative mental work and a minimum of physical effort. Eight letters were selected with the aid of a random number table. Each letter was represented in the table in proportion to its frequency of use in the English language. For example the letter "O" was assigned the random letters from 3173 to 3972 since it occurs 8.00% of the time (Gaines, 1956). In the selection of the eight letters, restrictions were made that no letter would occur more than twice, and there would be at least two but not more than five vowels. There were two sets of eight letters available to the subject during each period. He formed words from either set with the restriction of using only letters from one set in forming any specific word. Although both subjects in an experimental session had the same sets of letters, the sets were sequenced so that they did not have them at the same time. Any English word including names and places, but excluding abbreviations was permissible. If there was any doubt as to the acceptability of a word when the paper was scored, the American College Dictionary served as a standard for the grader. The criterion of performance was acceptable words formed per ten minute period.

Equipment:

1. Test Chamber: The experiment was performed at the Kansas State University American Society of Heating, Refrigeration and Air Conditioning Engineers (KSU-ASHRAE) Institute for Environmental Research Test Chamber. The test room is 12 ft. wide x 24 ft. long. All its interior surfaces are made of aluminum panels. The surface temperature of the panels is controlled by circulating chilled or heated water through copper tubes attached to the back of each panel.

2. Water Cooled Hood and Water Circulating System: The hood used in this experiment was different from the one used by Morales and Konz (1968). They used a canvas hood with rubber tubing glued on its inside surface. Since the hood covered the entire head and neck, a zipper, which ran from the forehead over the head to the neck was used to open it. This experimenter thought that their hood was suitable only for a specific head size and would not fit all heads, so it was decided to use one which would have better contact with the head for all people. A flexible rubber pad with flat oval tube with .024 inch walls manufactured by Gorman-Rupp Ind. Inc., model M-21, was used in this experiment. It covered most of the head area of the subject except for his face and forehead area; it did not cover the neck. The sides covered the ears and came down a little above the larynx (Plate I). It fitted tightly over most of the area it covered except for the top of the head. A compressor pump cooled the water while another pump kept water circulating through the hood at all times at the

PLATE I

Two subjects working anagrams in the heat, one wearing hood.

PLATE I

rate of approximately 0.26 gallons per minute.

The hood and the cooling system were relatively crude. The experimenter wished to keep water temperature at 39 F but, due to experimental problems, the water temperature varied from 37 to 56 F.

3. <u>YSI Rectal Probe</u>: A Yellow Springs Model 401 rectal probe was used to measure rectal temperature. This is a flexible precision temperature transducer about 3/32" inch O.D. which was inserted into the subject's anal canal to the depth of six inches.

4. <u>YSI Thermistors</u>: The Yellow Springs Model 409 thermistors were used to measure skin temperature. These thermistors have a sensitive area 3/8 inch in diameter. They were taped on the skin of the subjects, one on each anterior thigh, on each forearm, above each eyebrow, behind each ear and on the throat, care being taken so that they were not placed too tightly on the skin (to prevent readings from being influenced by the blood stream) and that they were fully covered by the adhesive tape (to prevent the readings being influenced by the environmental temperature).

5. <u>Thermometer and Recording System</u>: The ten thermistor leads from each subject were plugged in a previously designated box (Plate II). The leads from the box were connected to a United Systems Corporation Digital Thermometer, Model 500, with a range of 59 to 122 F which provided an instantaneous visual display to the nearest 0.1 F. A United Systems Corporation Digitec Recorder printed the information from the digital thermometer in a four digit column. The sensor

PLATE II

Two subjects working anagrams in the neutral environment

PLATE II

number and subject number was entered into the printer by the United Systems Corporation Manual Identification Unit Model 651. Thus, the output of this system was composed of a paper tape printed with two four digit columns. One column gave the subject number and the specific sensor number and the other the temperature registered by the sensor. Every five minutes the time was recorded on the page.

6. <u>Strip Chart Recorder and Heart Rate Sensors:</u> Three surface electrodes were glued to the chest of subject to detect his heart beat. Their leads were plugged into a box attached to the waist of the subject. The leads from the box were connected to the strip-chart recorder, where his electrocardiogram was recorded every two minutes for nine seconds. While taking the reading, subject number and time were entered on the paper tape. Output of an EKG is shown in Fig. 2. See also Plate III.

7. <u>Beam Balance Platform:</u> A Fairbanks Morse & Co. beam balance platform scale with an accuracy of 10 grams calibrated by the State of Kansas Bureau of Weights and Measurements was used to weigh the subjects.

<u>Subjects:</u> Eight male American undergraduate students were paid by the hour. See Table 1.

<u>Experimental Design:</u> The experiment was run for eight days from one to five P.M. in March and April, 1968. Wiring the subjects and getting other things ready took one hour on each day, before the actual experiment started. Therefore only three hours were available each day for obtaining

PLATE III

Strip chart recorder and thermometer and recorder system.

PLATE III

Table 1

Subject Characteristics

Subject	Age, Years	Weight, pounds	Height, inches	Dubois Body Area, square meters
1	20	145.0	68.0	1.78
2	20	161.6	67.5	1.86
3	20	119.0	65.5	1.60
4	20	132.0	70.0	1.75
5	18	266.2	74.5	2.49
6	19	189.0	71.0	2.06
7	22	170.0	73.2	2.01
8	19	137.4	68.0	1.74

the data. To collect base line data it was decided to run the subjects for one hour in the neutral, ET of 70 F (76 F dry bulb, 50% RH and air velocity less than 50 ft. per min.), and two hours in the heat, 93 F ET (100 F dry bulb, 70% RH and air velocity less than 50 ft. per min.), the recommended physiological limit (Wing, 1965).

Experimental Sequence: Subject 1, 3, 5 and 7 had the hood on the first day and no hood on the second day; subject 2, 4, 6 and 8 had the reverse sequence.

Experimental Procedure: Each subject was weighed nude, had his height recorded, and then was equipped with a rectal probe, one temperature sensor on each anterior thigh above the vastus medialis muscle, one on each forearm, above the brachioradialis muscle and five sensors on his head (above each eyebrow, behind each ear and on the throat). In addition, heart rate sensors were attached. He then was weighed with clothing and sensors. The following indices of physiological cost then were available: rectal, limb and head temperatures; heart rate, standard deviation of instantaneous heart rate; sweat rate and exposure time.

Two subjects were run at a time. Both subjects composed words in the pretest room for one hour while performance and baseline data was recorded. Then both entered the environmental room but only one subject wore the hood. Plate I. They composed words for two hours, and then they returned to the pretest room, were weighed again, disrobed and removed sensors, and were permitted to dress and leave.
Each subject was run two times, once wearing the hood and a second

time without the hood or vice versa.

They were permitted to drink water, but this water was subtracted from their final weight in the calculation of sweat loss. The subjects wore socks and Bermuda shorts.

<u>Measurements</u>: Rectal temperature was measured with a rectal probe inserted to the depth of 6 inches. The average of the four limb sensors was taken as limb temperature. The average of the five head sensors was taken as the head temperature. The temperatures were recorded every five minutes on a printed tape along with the appropriate sensor number.

The electrocardiogram was recorded for a nine second period every two minutes. Output of the strip chart recorder is shown in Fig. 2. The distance between successive "r" waves was measured with a scale, converted into seconds (time interval between heart beats), then beats per minute, standard deviation of instantaneous heart rate and percent coefficient of variation of heart rate. The computation is shown below:

X_i = interval between each heart beat in seconds

where

$i = 1$ to n, the value of i varied from 12 to 18 during the nine second period.

Mean X (seconds) = Sum X_i/n

Beats per Minute = 60/Mean X

Variance = Sum $(X_i - \text{Mean X})^2/n$

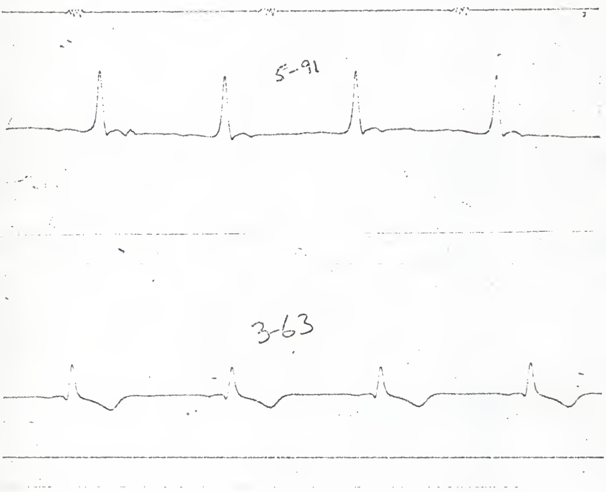

Fig. 2. EKG Output of strip chart recorder.

Standard deviation = Square root variance

Coefficient of variation = Standard deviation/Mean X

The water temperature at the inlet and outlet of the hood was recorded from time to time as well as the flow rate of the water. The water temperature in these experiments had a mean value of 43 F with a flow rate of approximately 0.26 gallon (1.0 liter) per minute and temperature differential of 6 F between the inlet and outlet water. The heat absorbed by the hood was estimated as 3.3 Kcal. by the following formula:

1. Heat absorbed by the hood =

$$\frac{\text{Water flow rate (liters per min.) x temp. diff. (°F) x 1.0 Btu x .252 (Kcal per Btu)}}{\text{.4536 (liters per lb.) x lb. x °F}}$$

$$\frac{1.0 \times 6 \times .252}{.4536} = 3.3 \text{ Kcal per minute}$$

Each subject was weighed when he began the experiment in the neutral and again when he came out of the heat room. The difference in these two weights was converted to weight lost in grams per hour per square meter of body area and heat lost in sweat converted to Kcal per hour by the following formula:

2. Weight loss, grams per hour per square meter of body area =

$$\frac{\text{Weight loss (lbs.) x 453.6 (grams per lb.)}}{\text{Exposure time (hours) x Body area } (m^2)}$$

3. Heat loss in sweat, Kcal per hour =

Weight loss in sweat (grams per hour) x .575 (Kcal per gram)

4. Heat removed by hood, Kcal per hour =

Sweat loss without the hood, Kcal per hour
- Sweat loss with the hood, Kcal per hour

RESULTS

On the fifth day of the experiment, one subject who came for the first time got sick and started vomitting before the experiment began, so he was let go and another subject called. On that day the experiment was run for only two hours, 30 minutes in the neutral and 90 minutes in the heat (subject five with the hood and six without the hood). Therefore only seven subjects were scheduled for 120 minutes in the heat with and without the hood. Without the hood, two out of the seven subjects (subject one after 105 minutes in the heat and subject eight after 80 minutes) complained of severe headaches, their faces flushed, and their rectal temperature increased as much as 1.4 F while their head temperature exceeded rectal and skin temperature increased by as much as 6.5 F. Therefore, upon their request, they were removed from the environmental room. With the hood, all seven completed 120 minutes of exposure.

The hood absorbed approximately 198.0 Kcal. per hour (782.0 Btu per hour) as calculated from equation (1). The hood removed 56.7 Kcal per hour (224.0 Btu per hour) from the man as calculated from equation (4), indicating that only 29% of the heat was removed from the man and the remaining 71% from the environment.

Productivity:

Words created in the first 20 minutes of the neutral and of the heat was recorded but not used since it had the typical initial transients due to nervousness and learning. Table 2 shows the average number of words formed per 10 min. in the neutral and heat stress with and without the hood. The average productivity was 26.2 words in the neutral condition before the hood was worn. Working in the heat with the hood caused a degradation of 2.98 words (11.4%). A Wilcoxon Matched-Pairs Signed Rank test showed that this was not significantly ($p < .05$) different from the neutral. The average productivity was 26.9 words in the normal condition before no hood was worn. Working in the heat without the hood caused a degradation of 5.05 words (19.5%). This output was significantly ($p < .05$) lower than the neutral as checked by the Wilcoxon test.

Temperatures:

Rectal Temperature: As soon as the recording of subjects' baseline data in the neutral room began, their rectal temperature started dropping (Fig. 3 to Fig. 10) except for subject three (Fig. 5) on his first day (Table 3). The average drop was 0.48 F on the days before the hood was worn and 0.55 on the days when no hood was worn; the difference was not significant ($p < .05$). A Wilcoxon text showed that the .48 F and .55 F were significantly different ($p < .05$) from zero. This drop in rectal temperature continued after the subjects entered the heat room

Table 2

Words per ten minutes by condition for each of the eight subjects.

Subject	Condition			
	Neutral, before hood	Heat, Hood	Neutral, before No Hood	Heat, No Hood
1	23.8	20.9	30.2	19.7
2	30.2	25.2	25.5	26.2
3	16.5	19.4	21.0	19.1
4	21.3	13.8	20.8	13.5
5	22.5	23.4	26.5	22.1
6	30.8	25.3	26.5	21.8
7	33.0	28.0	39.5	30.2
8	31.3	29.6	25.8	23.8
Average	26.2 (100%)	23.2 (88.6%)	26.9 (100%)	22.1 (80.5%)

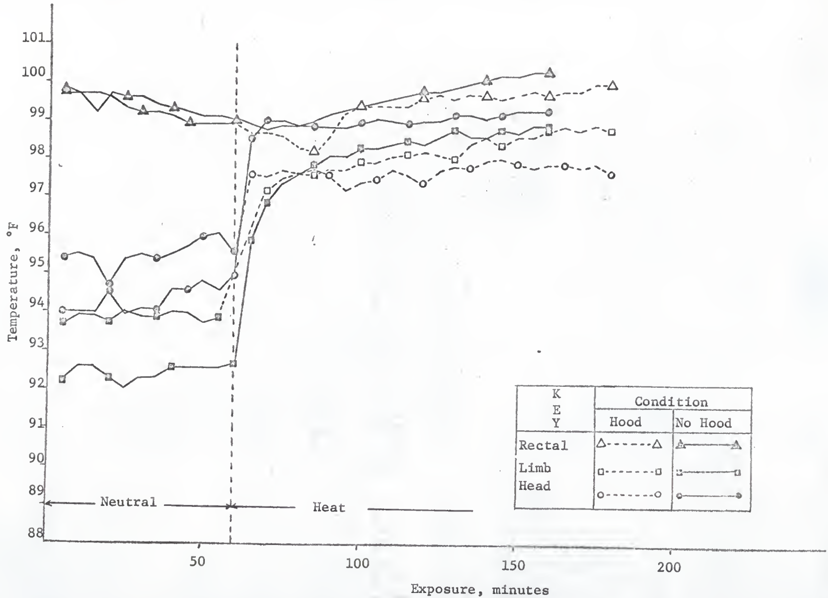

Fig. 3. Rectal, limb and head temperature in the neutral and heat environment for subject 1.

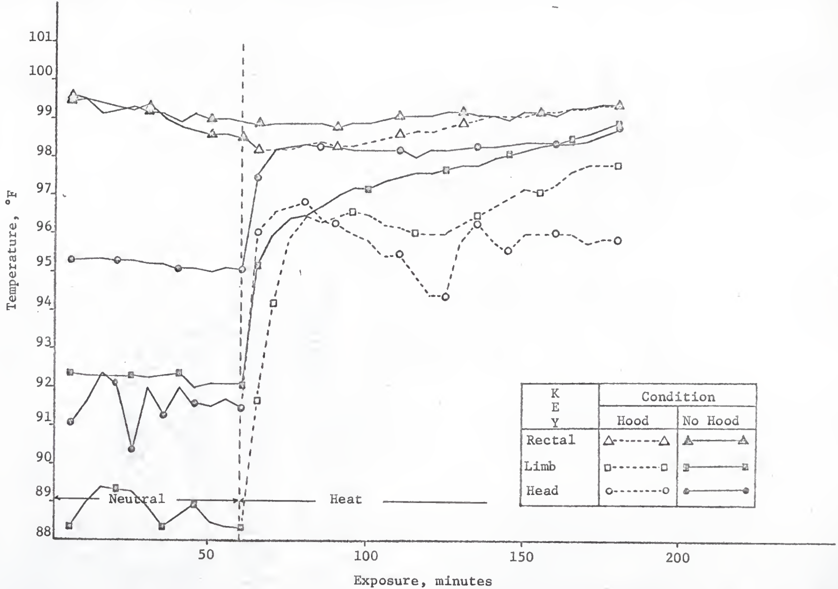

Fig. 4. Rectal, limb and head temperatures in the neutral and heat environment for subject 2.

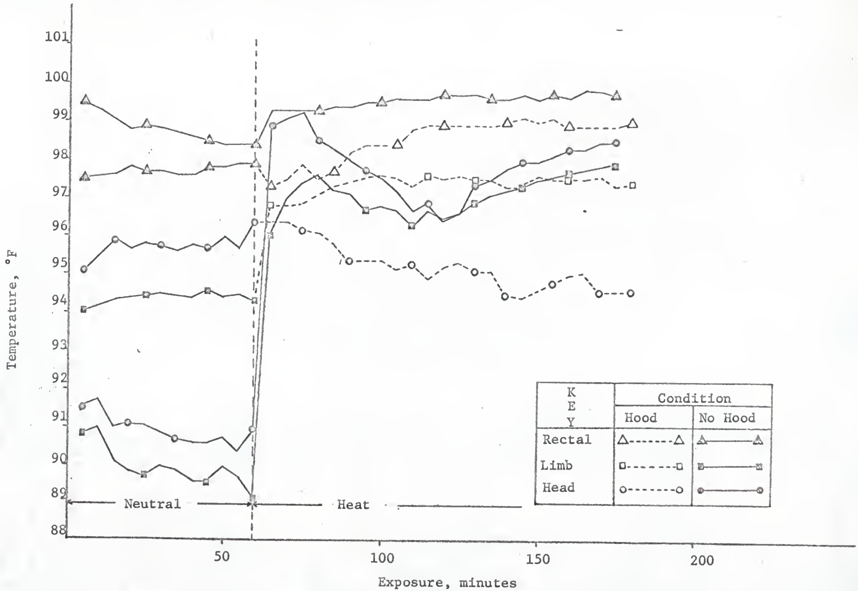

Fig. 5. Rectal, limb and head temperature in the neutral and heat environment for subject 3.

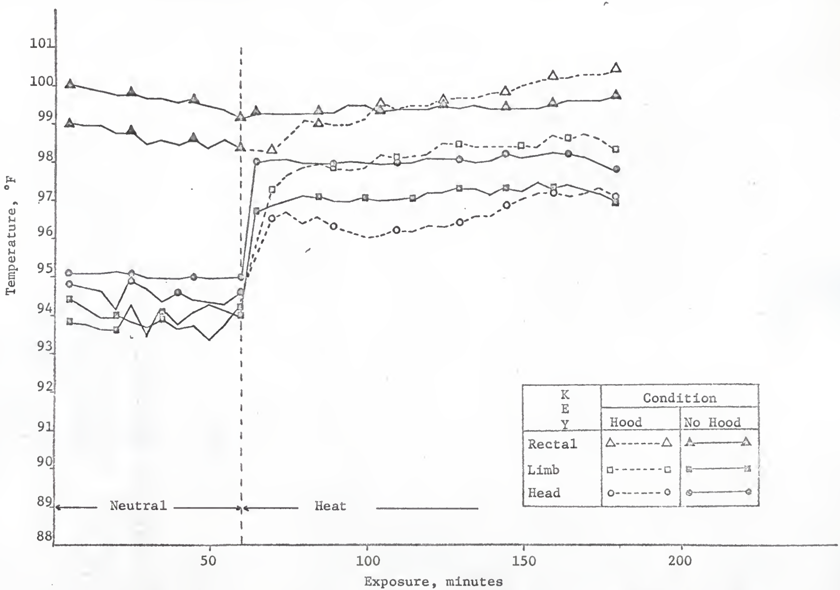

Fig. 6. Rectal, limb and head temperature in the neutral and heat environment for subject 4.

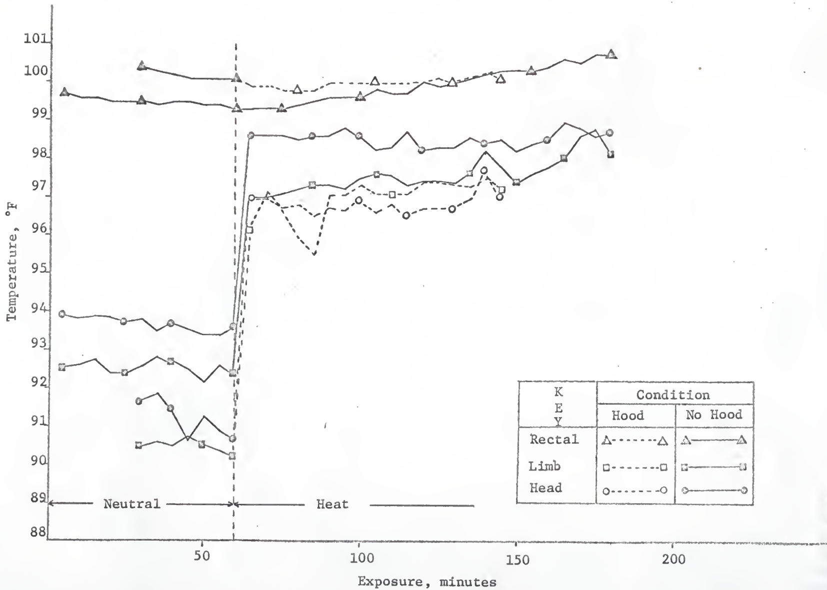

Fig. 7. Rectal, limb and head temperature in the neutral and heat environment for subject 5.

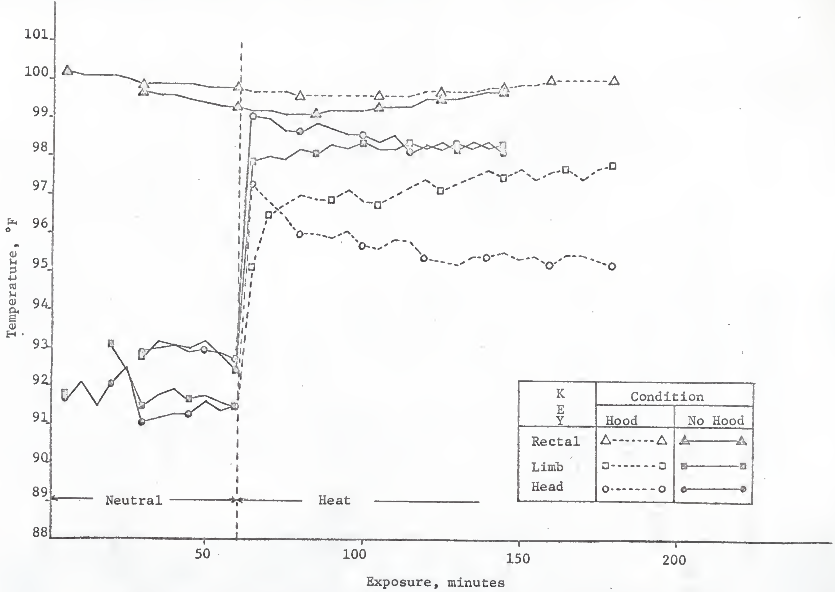

Fig. 8. Rectal, limb and head temperature in the neutral and heat environment for subject 6.

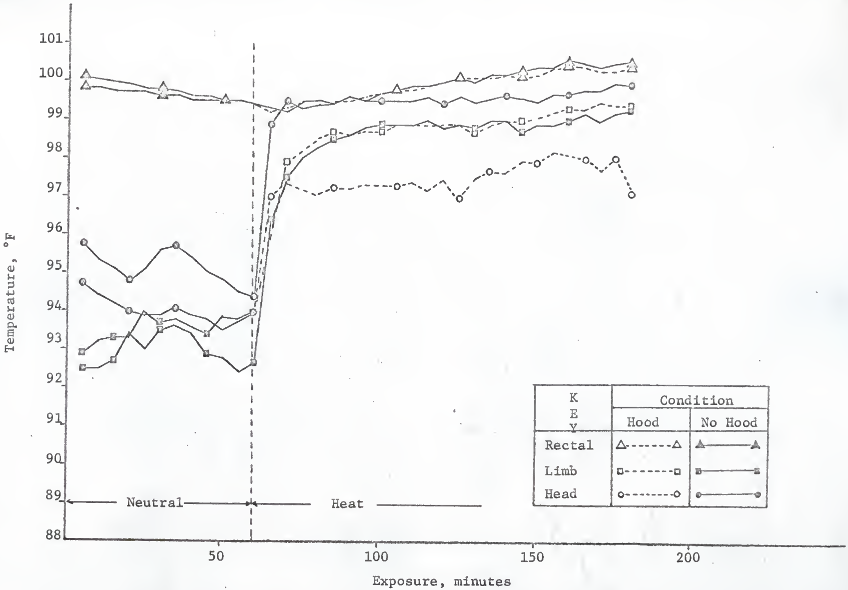

Fig. 9. Rectal, limb and head temperature in the neutral and heat environment for subject 7.

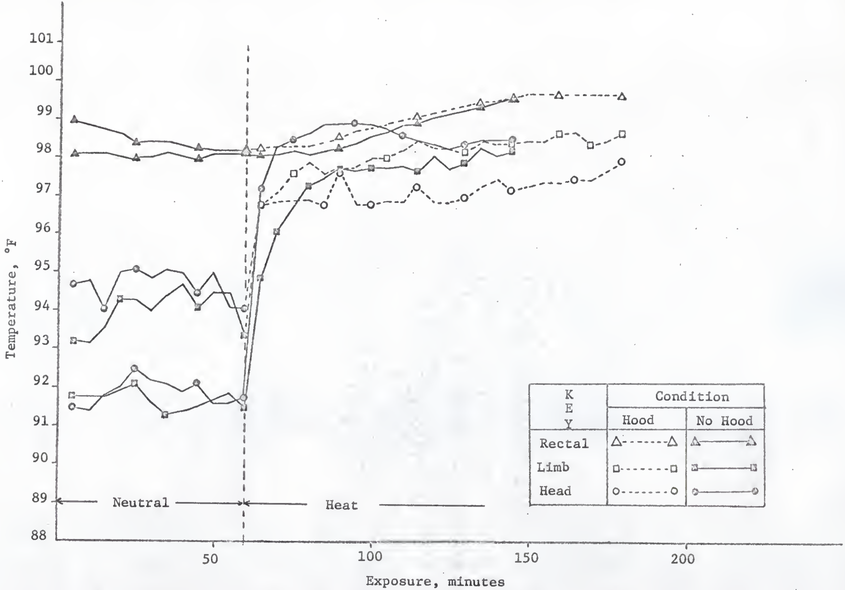

Fig.10. Rectal, limb and head temperature in the neutral and heat environment for subject 8.

Table 3

Decrease in rectal temperature (°F) in the neutral for each of the eight subjects.

Subject	Exposure time, minutes	Condition	
		Neutral, before Hood	Neutral, before No Hood
1	60	0.9	0.7
2	60	1.1	0.5
3	60	-0.4	1.1
4	60	0.6	0.8
5	30	0.3	0.2
6	30	0.1	0.4
7	60	0.4	0.7
8	60	0.8	0.0
Average		0.48	0.55

before it started rising.

Rectal temperature in the heat increased over the neutral and was significantly ($p < .05$) higher as checked by the Wilcoxon test whether the hood was worn or not. (Fig. 3 to Fig. 10). Table 4 shows rectal temperature at the end of exposure with and without the hood for each subject. The average terminal rectal temperature of 99.8 F with the hood was not significant ($p < .05$) from the 99.9 F without the hood. From Fig. 3 to Fig. 10 it is clear that after sometime the rise in rectal temperature with the hood either stopped or was very slow, but without the hood the trend continued rising.

Head Temperature: The head temperature in the heat was significantly higher than the normal whether the hood was worn or not. Fig. 3 to Fig. 10 show that the hood kept the head temperature below rectal and limb. Without the hood head temperature either equalled or exceeded rectal and limb temperature. After some time of exposure the hood kept head temperature fairly constant while, without the hood, head temperature had a rising trend. The average terminal head temperature of 98.7 F without the hood was significantly ($p < .05$) greater than the 96.5 F with the hood. (Table 5). The hood kept head temperature 3.3 F below the rectal whereas without the hood it was only 1.2 F below the rectal. Note that the hood kept the head temperature below the limb temperature whereas without the hood it always exceeded limb temperature.

Limb Temperature: Limb temperature in the heat was significantly higher over the normal whether the hood was worn or not. Fig. 3 to Fig. 10 shows that limb temperature was not affected much with the hood. An average limb temperature of 98.1 F with the hood was not

Table 4

Rectal temperature (°F) at the end of exposure for each of the eight subjects.

Subject	Exposure time, minutes	Condition		At the end of 80 min.	
		Hood	No Hood	Hood	No Hood
1	105	99.7	100.3	99.6	100.2
2	120	99.4	99.4	99.1	99.0
3	120	98.9	99.7	99.1	99.7
4	120	100.4	99.7	99.8	99.4
5	80	100.1	100.3	100.1	100.3
6	85	99.8	99.7	99.8	99.7
7	120	100.4	100.5	100.1	100.3
8	80	99.6	99.6	99.6	99.6
Average		99.8	99.9	99.4	99.8

Table 5

Head temperature (°F) at the end of exposure
for each of the eight subjects.

Subject	Exposure time, minutes	Condition		At the end of 80 min.	
		Hood	No Hood	Hood	No Hood
1	105	97.9	99.3	98.0	99.2
2	120	95.9	98.8	95.6	98.4
3	120	94.6	98.5	94.5	98.0
4	120	97.1	97.8	97.0	98.2
5	80	97.0	98.5	97.0	98.5
6	85	95.5	98.2	95.5	98.2
7	120	97.1	100.0	98.0	99.6
8	80	97.2	98.5	97.2	98.5
Average		96.5	98.7	96.6	98.6

significantly ($p < .05$) different from the 98.3 F without the hood. (Table 6). Limb temperature was 1.7 F below rectal with the hood and 1.6 F without the hood.

Sweat Rate:

Table 7 shows the sweat rate with and without the hood for each subject. It was assumed (Fanger,1967) that the subject in the neutral had a metabolic rate of 50 Kcal. per hour per square meter of body area and lost 15 Kcal. per hour per square meter of body area as insensible perspiration and skin diffusion. Therefore, while finding the sweat rate, this loss in the neutral was converted to grams per hour per square meter of body area and subtracted from the total sweat loss (difference in two weights). In the heat stress without the hood subjects lost an average of 148.4 grams per hour per square meter of body area but only 97.7 grams with the hood. Apparently the body, when it had the hood, sweated at 66% of the rate it sweated without the hood. With the hood, the body lost 111.2 Kcal. per hour in sweat, whereas without the hood it lost 167.9 Kcal per hour. (Table 7). This indicates the hood removed about 56.7 Kcal (224.0 Btu) per hour from the subject.

Heart Rate:

The data for the first 30 minutes in the neutral was recorded and plotted but not used as basal level since it is often affected by nervousness. Basal level was taken as the average heart rate between 31-60 minutes of exposure; that is, the last 30 minutes of the neutral condition. Fig. 11 to Fig. 18 show that the heart rate increased with

Table 6

Limb temperature (°F) at the end of exposure for each of the eight subjects.

Subject	Exposure time, minutes	Condition		At the end of 80 min.	
		Hood	No Hood	Hood	No Hood
1	105	98.6	98.7	98.4	98.8
2	120	97.8	98.9	96.9	98.1
3	120	97.3	97.9	97.3	97.3
4	120	98.3	97.0	98.3	97.3
5	80	97.2	97.8	97.2	97.8
6	85	97.5	98.3	97.5	98.3
7	120	99.4	99.3	99.0	98.7
8	80	98.4	98.2	98.4	98.2
Average		98.1	98.3	97.3	98.1

Table 7

Weight loss and heat removed by evaporation of sweat for each of the eight subjects.

Subject	Exposure time, minutes		Cooling water temperature °F	Weight loss, grams/hr./m^2 of body area		Heat removed by sweating, Kcal./hr.	
	Hood	No Hood	Hood	Hood	No Hood	Hood	No Hood
1	120	105	52	123.3	187.5	126.2	191.9
2	120	120	44	55.2	145.5	59.0	155.6
3	120	120	41	108.9	118.8	100.1	109.3
4	120	120	45	28.5	102.3	28.6	102.9
5	80	120	50	184.1	248.4	263.5	355.6
6	120	85	45	100.4	151.1	118.9	179.0
7	120	120	45	77.2	98.7	89.2	114.1
8	120	80	45	104.4	134.9	104.4	135.0
Average				97.7	148.4	111.2	167.9

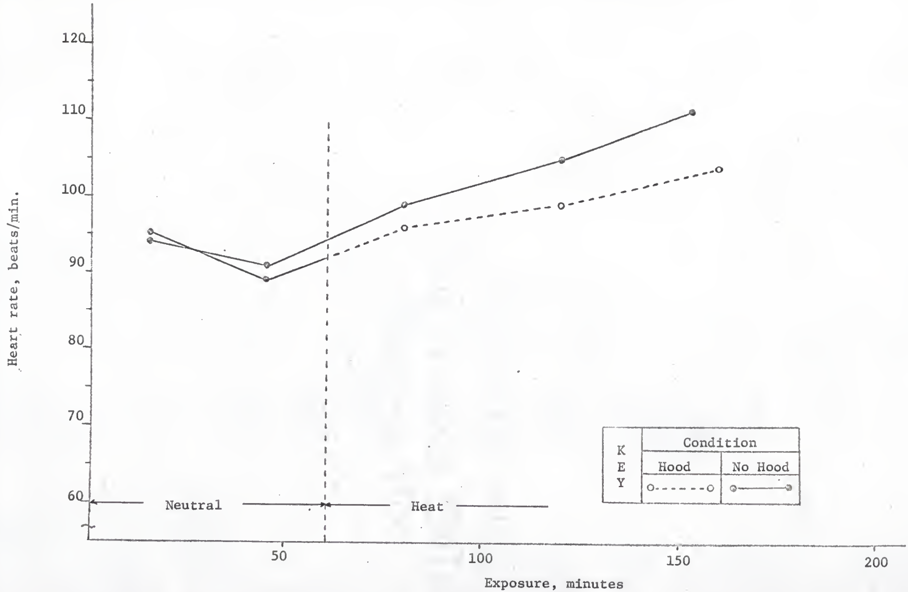

Fig. 11. Heart rate for the neutral and heat environment for subject 1.

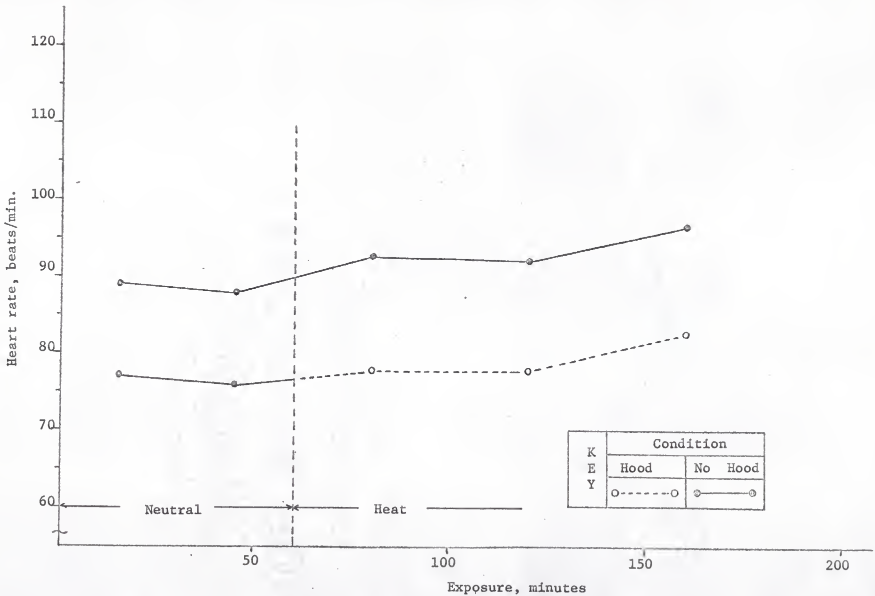

Fig. 12. Heart rate for the neutral and heat environment for subject 2.

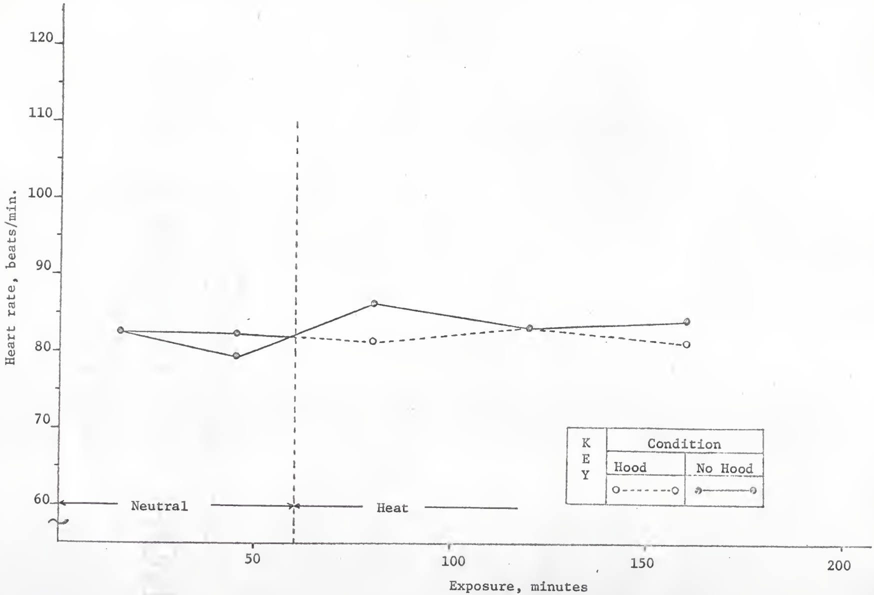

Fig. 13. Heart rate for the neutral and heat environment for subject 3.

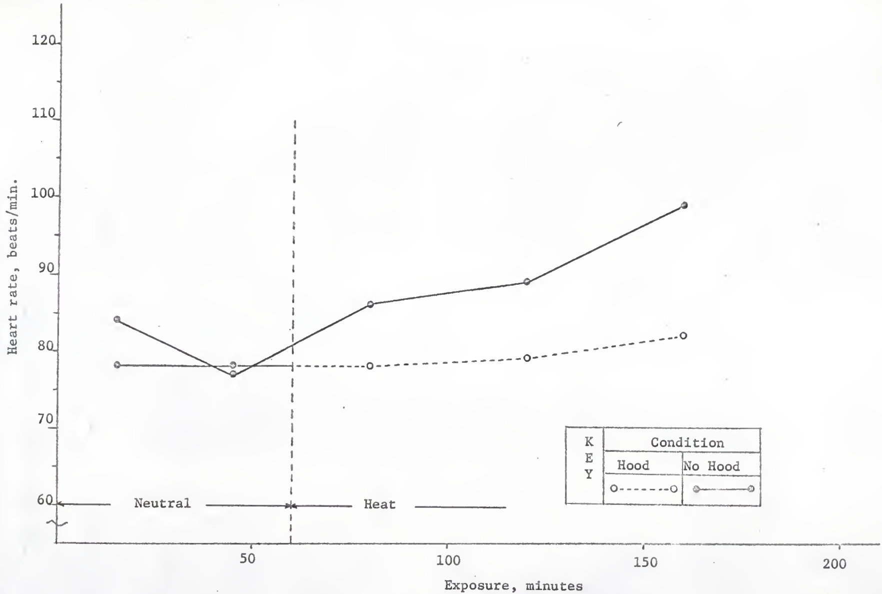

Fig. 14. Heart rate for the neutral and heat environment for subject 4.

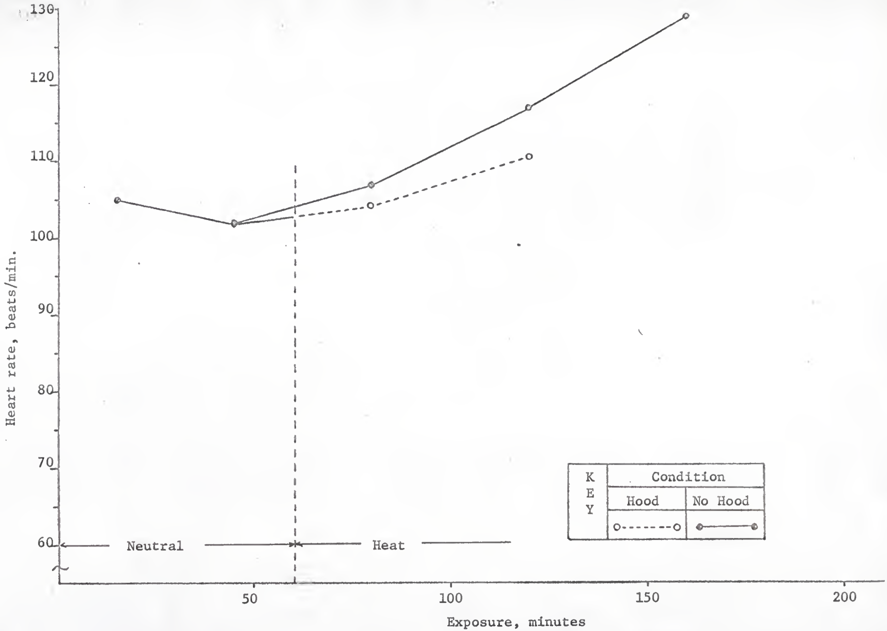

Fig. 15. Heart rate for the neutral and heat environment for subject 5.

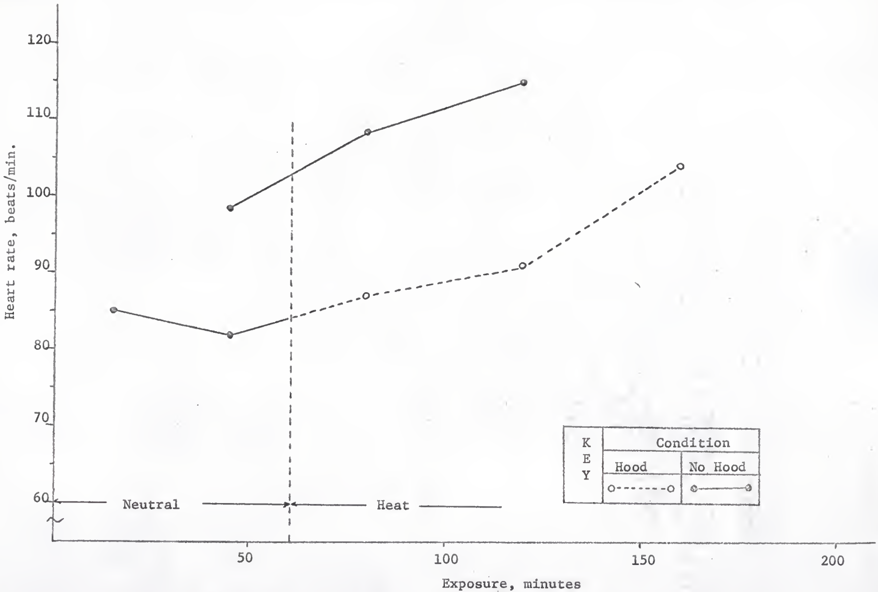

Fig. 16. Heart rate for the neutral and heat environment for subject 6.

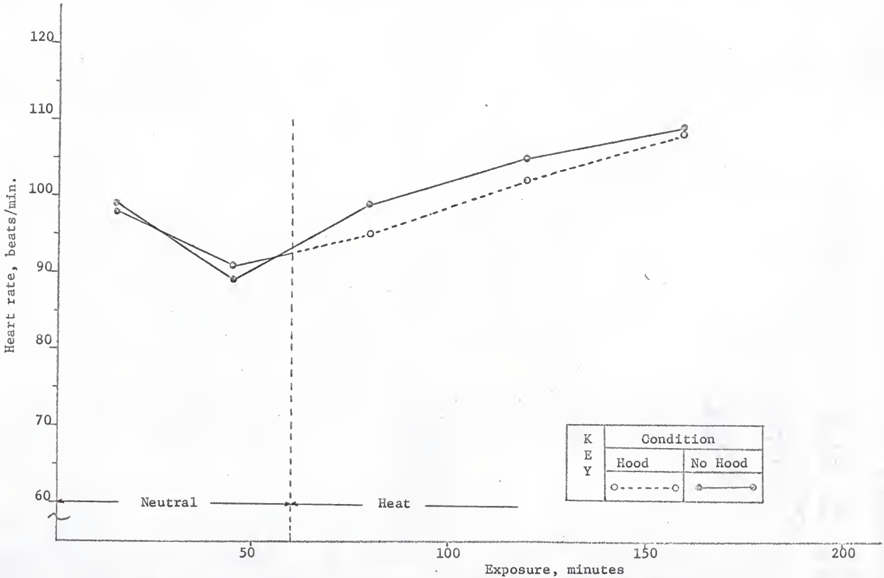

Fig. 17. Heart rate for the neutral and heat environment for subject 7.

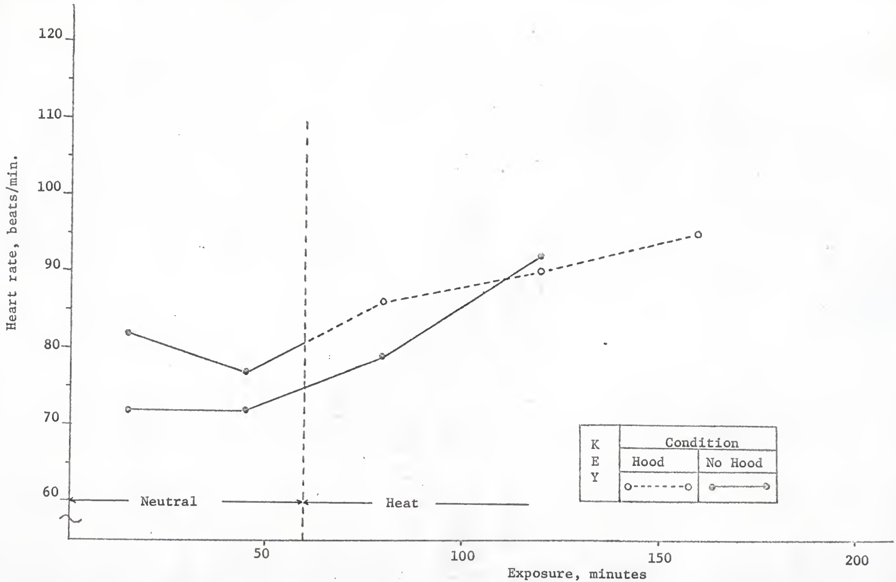

Fig. 18 . Heart rate for the neutral and heat environment for subject 8.

an increase of exposure time. Table 8 shows that the average heart rate between the exposure time of 61-100, 101-140 and 141-180 minutes was 88, 90 and 92 beats per minute with the hood and 94, 98 and 104 beats per minute without the hood. A Wilcoxon test showed that the average heart rate between these three exposure times was significantly ($p < .05$) greater than the basal level. Further it was found that the average heart rate of each of these three exposure times with the hood was significantly lower than without the hood. The average exposure heart rate of 98 beats per minute without the hood was significantly ($p < .05$) greater than the 90 beats per minute with the hood.

To find other indices of stress, the standard deviation of instantaneous heart rate and percent coefficient of variation of heart rate were calculated. (Kalsbeek and Ettema, 1965).

The standard deviation was also taken as the average value at 31-60 minutes. As is seen from Table 9 and Fig. 19 to Fig. 26 the standard deviation decreased with the increase of exposure time. Table 9 shows that, at different exposure times, the standard deviation was larger with the hood than without the hood. With the hood the average value of the standard deviation was significantly ($p < .05$) lower than normal only between the exposure of 141 - 180 min. It was lower at 61 - 100 and 101 - 140 minutes but not significantly. Without the hood it was lower than the normal between 61 - 100 min. (not statistically significant though) but was significantly lower than the normal for the exposure of 101 - 140 and 141 - 180 minutes. With the hood, for the exposure of 61 - 100 min. the standard deviation was not significant ($p < .05$) from the no hood but between 101 - 140 and 141 - 180 min. it was significantly lower

Table 8

Heart rate (beats/min.) for each subject of the eight subjects.

Subject	Exposure time, minutes							
	31 to 60		61 to 100		101 to 140		141 to 180	
	NeH	NeNH	H	NH	H	NH	H	NH
1	89	91	96	99	99	105	104	111
2	76	87	78	93	78	93	83	97
3	82	79	81	86	83	83	81	84
4	78	77	78	86	79	89	82	99
5	102	102	104	107	111	117	*	129
6	82	98	87	108	91	115	104	*
7	91	89	95	99	102	105	103	104
8	77	72	86	79	90	92	95	*
Average	85	86	88	94	90	98	92	104

*Data not available

KEY:

NeH Neutral before hood

NeNH Neutral before No Hood

H With Hood

NH No Hood

($p < .05$) without the hood than with the hood. The average exposure standard deviation of instantaneous heart rate of .024 secs. without the hood was significantly ($p < .05$) lower than the .027 secs. with the hood. This shows that the hood kept the standard deviation of instantaneous heart rate higher whereas without it it kept on dropping, indicating less mental strain with the hood than without the hood.

Table 10 shows the percent coefficient of variation of heart rate with and without the hood. As seen from Table 10, the coefficient also kept decreasing with increase in exposure time. With the hood it was lower than the basal level (not statistically lower) between the exposure of 61 - 100 and 101 - 140 min. but significantly ($p < .05$) lower than the basal between 141 - 180 min. Without the hood it decreased more and was non-significant from the basal level only between 61 - 100 min. but significantly ($p < .05$) lower between 101 - 140 and 141 - 180 min. exposure. Further a Wilcoxon test showed that percent coefficient of variation with the hood was non-significant from no hood only between 61 - 100 but was significantly ($p < .05$) higher between 101 - 140 and 141 - 180 min. exposure. The average exposure percent coefficient of variation of heart rate of 3.9% without the hood was significantly ($p < .05$) lower than the 4.2% with the hood. This indicates that, in the heat, the coefficient of variation of heart rate kept decreasing without the hood whereas the hood kept it fairly high.

DISCUSSION

While working in the heat without the hood performance deteriorated

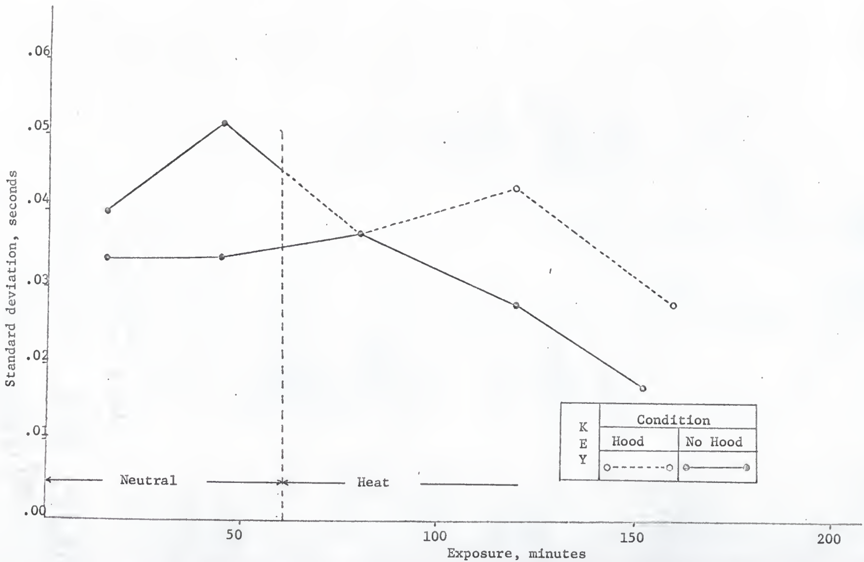

Fig. 19. Standard deviation of instantaneous heart rate in the neutral and heat environment for subject 1.

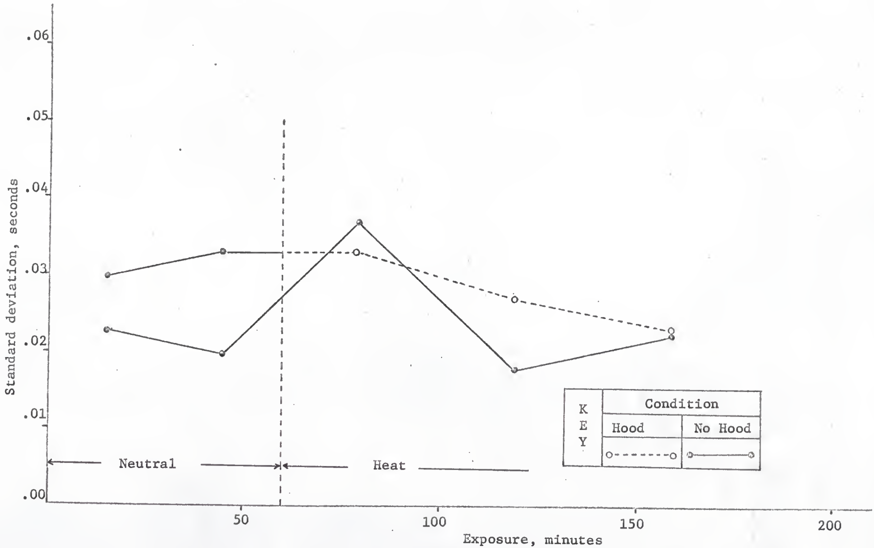

Fig. 20. Standard deviation of instantaneous heart rate in the neutral and heat environment for subject 2.

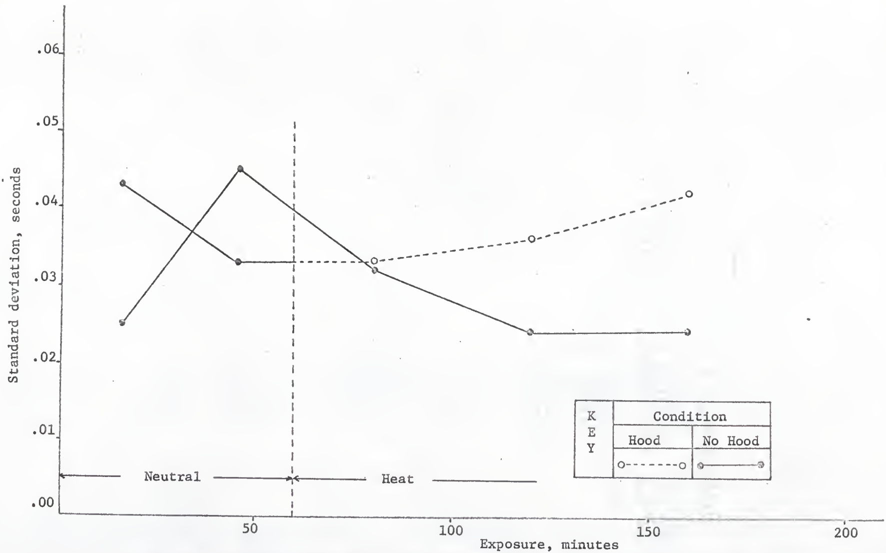

Fig. 21 Standard deviation of instantaneous heart rate in the neutral and heat environment for subject 3.

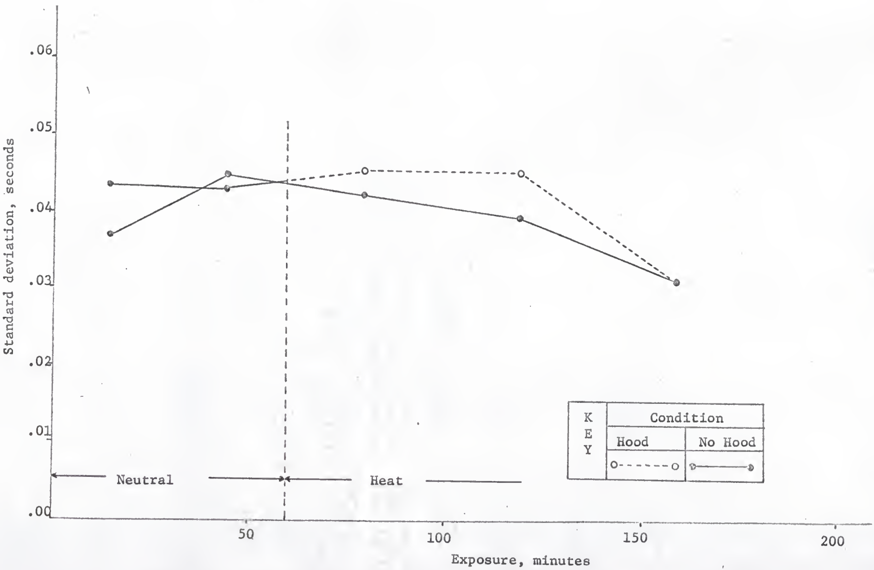

Fig. 22. Standard deviation of instantaneous heart rate in the neutral and heat environment for subject 4.

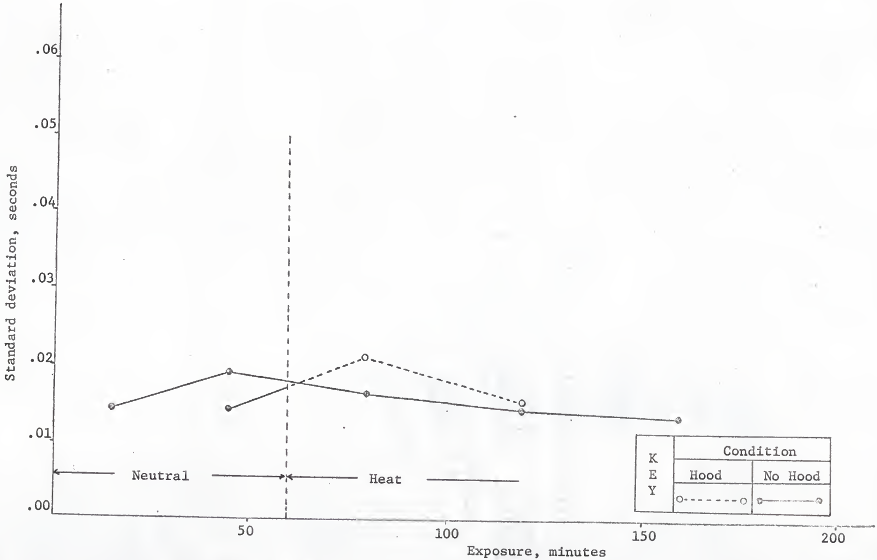

Fig. 23. Standard deviation of instantaneous heart rate in the neutral and heat environment for subject 5.

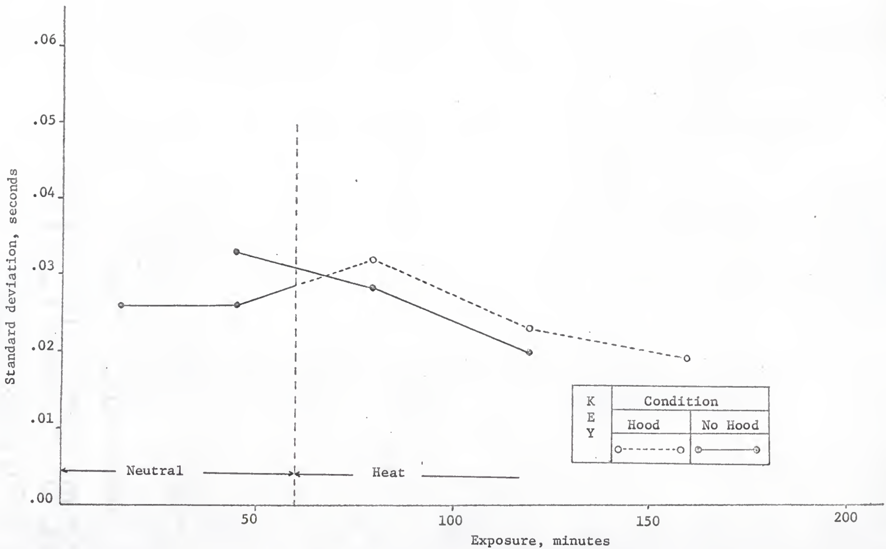

Fig. 24. Standard deviation of instantaneous heart rate in the neutral and heat environment for subject 6.

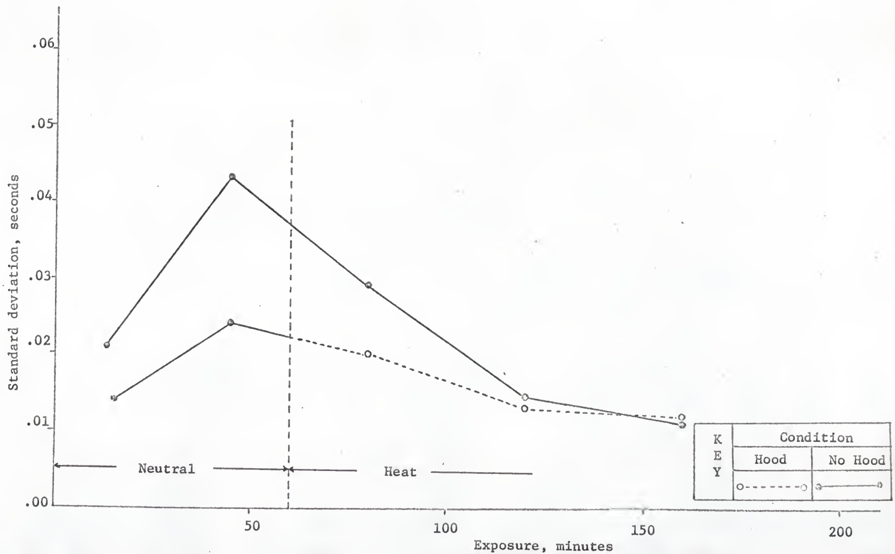

Fig. 25. Standard deviation of instantaneous heart rate in the neutral and heat environment for subject 7.

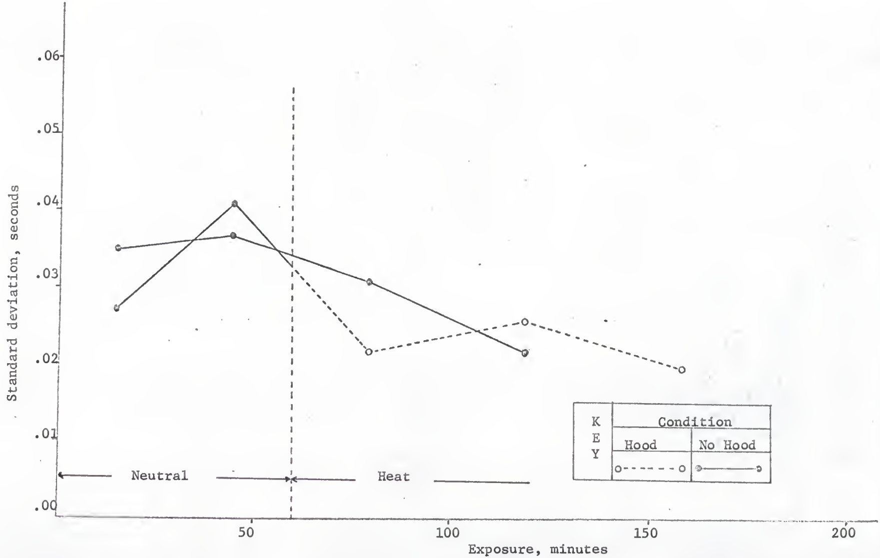

Fig. 26. Standard deviation of instantaneous heart rate in the neutral and heat environment for subject 8.

Table 9

Standard deviation (seconds between beats) of instantaneous heart rate for each of the eight subjects.

Subject	Exposure time, minutes							
	31 to 60		61 to 100		101 to 140		141 to 180	
	NeH	NeNH	H	NH	H	NH	H	NH
1	.052	.034	.037	.037	.043	.028	.028	.017
2	.033	.020	.033	.037	.027	.018	.023	.022
3	.033	.045	.033	.032	.036	.024	.042	.024
4	.043	.045	.045	.042	.045	.039	.031	.031
5	.014	.019	.021	.016	.015	.014	*	.013
6	.026	.033	.032	.028	.023	.020	.019	*
7	.024	.043	.020	.029	.013	.014	.013	.011
8	.041	.037	.022	.031	.026	.022	.020	*
Average	.033	.035	.030	.031	.029	.022	.025	.020

*Data not available

KEY:

NeH Neutral before hood

NeNH Neutral before No Hood

H With hood

NH No hood

Table 10

Heart rate coefficient of variation (percent) for each of the eight subjects.

Subject	Exposure time, minutes							
	31 to 60		61 to 100		101 to 140		141 to 180	
	NeH	NeNH	H	NH	H	NH	H	NH
1	7.7	5.1	5.9	6.1	7.0	4.8	4.9	3.2
2	4.2	2.9	4.2	5.2	3.5	2.7	3.2	3.5
3	4.5	6.0	4.4	4.6	5.0	3.3	5.6	3.3
4	5.5	5.7	5.8	7.1	6.0	5.8	4.2	5.1
5	2.3	3.2	3.7	2.9	2.8	2.7	*	2.7
6	3.5	5.4	4.6	5.1	3.5	3.8	3.3	*
7	3.6	6.4	3.1	4.7	2.2	2.5	2.1	2.1
8	5.3	4.4	3.2	4.1	4.0	3.4	3.1	*
Average	4.6	5.0	4.4	4.9	4.3	3.7	3.9	3.3

*Data not available

KEY:

NeH	Neutral before Hood
NeNH	Neutral before No Hood
H	With hood
NH	No hood

significantly which is agreement with the literature. It is interesting to note that performance in the heat with the hood was not significant from the neutral. This indicates that the hood did help the subjects keep statistically normal performance whereas without the hood performance deteriorated significantly from the normal.

An interesting outcome of this experiment is the drop in rectal temperature in the neutral, which was quite unexpected to the author. Hendler (1963) states that some discrete regions in the brain act as "centers" in initiating, modifying, or arresting certain bodily functions usually associated with thermoregulation. Either the subjects anticipated going into the heat and this psychological fear of going into the heat made the rectal temperature drop, or the metabolic rate before starting the experiment, as compared to during experimental session in the neutral, was different. However, in the heat, the subjects could not prevent the rise. The rectal temperature at the end of exposure with and without the hood was either equal or higher than the temperature at the beginning of the experiment. This drop in rectal temperature in the neutral indicates that the body can regulate its own temperature. With and without the hood rectal temperature was statistically the same.

The head temperature in the heat increased significantly over the initial level which is in agreement with the literature. A lower head temperature with the hood than without the hood is in agreement with Morales and Konz (1968). This indicates that the hood functions as a good conductor. It is expected that without the hood at longer exposure times head temperature will increase to a value so that the subjects will not be able to stay in the heat.

The hood did not keep limb temperature lower than without the hood, which was quite unexpected. There is no rigid explanation for this except that limb temperature varied too much between days in the neutral, perhaps due to varied temperature in the neutral which might have affected the limb temperature in the heat.

A higher sweat rate without the hood than with the hood is in agreement with Morales and Konz (1968) who also found the same type of results. Quite unexpected that the sweat rate with this hood was higher than what Morales and Konz (1968) found. They found that their hood removed about 322 Kcal per hour from the man. It was expected that the heat removed with this hood in this mental kind of task would be more than 322 Kcal per hour. It seems that the new hood did not cool as well as the Morales and Konz model. Of course, the subjects, environmental and work conditions were not the same.

The heart rate with the hood was significantly lower than without the hood which is in agreement with Morales and Konz (1968). This indicates that with the hood the decreased heart rate may reflect the decreased requirement for blood to the peripheral regions (skin). The decreased sweat loss may be related to this reduced blood flow.

The higher standard deviation of instantaneous heart rate and the higher percent coefficient of variation of heart rate with the hood are other indices that show that, with the hood, subjects were experiencing less mental strain than they were without the hood.

The experiment reported here is significant in the sense that it presents several different mental and physiological responses of a subject doing work while cooled with a water cooled hood. This experiment gives information which is essential for the design of a control system which would do automatically what this experimenter did by hand during this experiment. Water cooling offers a powerful and beneficial means of removing body heat, enough to be able to keep up with the heat dissipation required by a man working in the heat. Further investigation should be made in this area by changing different variables such as thermal resistance of the tubes (Richardson, 1967), inlet water temperature, and the tube area touching the head.

SUMMARY AND CONCLUSIONS

The effect of a heat stress environment while doing creative mental work was investigated. Eight male American undergraduate students were exposed to a neutral environment (70 F ET, 76 F dry bulb, 50% RH and air velocity less than 50 ft. per minute) and a heat stress environment (93 F ET, 100 F dry bulb, 70% RH and air velocity less than 50 ft. per minute). Each subject was run twice, once wearing the hood in the heat and a second time without the hood or vice versa. They worked anagrams in the neutral for one hour and then in the heat for two hours.

It was concluded:

1. With the hood, performance was not significantly different from the normal whereas without the hood it was significantly lower than the normal.
2. Cardiac and mental strain appeared to be reduced more while wearing the hood than without the hood as measured from:
   a. Significantly lower heart rate with the hood than without the hood.
   b. Significantly higher standard deviation and percent coefficient of variation of heart rate with the hood than without the hood.
3. With the hood subjects lost less weight in sweat indicating a reduced contribution by this avenue of heat loss.
4. Rectal temperature and limb temperature was statistically the same with and without the hood.
5. Head temperature with the hood was significantly lower than without the hood indicating that heat loss via conduction is increased with the water-cooled blood.

The above factors (a lower head temperature, a lower heart rate, higher standard deviation and higher percent coefficient of variation of heart rate and reduced sweat rate) indicates that men working in the heat can be protected with a cooling hood without any undue side effects.

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THE PHYSIOLOGICAL AND PERFORMANCE RESPONSES WITH A WATER COOLED HOOD IN A HEAT STRESS ENVIRONMENT WHILE DOING CREATIVE MENTAL WORK

by

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B.Sc. (Electrical), Punjabi University, India, 1966

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Industrial Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1969

ABSTRACT

The effect of a water cooled hood in a heat stress environment upon subjects' physiological and performance responses at creative mental work was investigated. Eight male American undergraduate students worked anagrams for one hour in the neutral environment (ET of 70 F, 76 F dry bulb and 50% RH) and then in the heat stress environment (ET of 93 F, 100 F dry bulb and 70% RH) for two hours. Each subject was run twice, once wearing the hood and a second time without the hood or vice versa.

1. Productivity decreased a non-significant 11.4% with the hood, whereas without the hood it decreased significantly 19.5% ($p < .05$).
2. With the hood the body lost only 97.7 grams per hour per square meter of body area in sweat whereas without the hood it lost 148.4 grams.
3. Rectal and limb temperatures with and without the hood were statistically the same, whereas head temperature of 98.7 F without the hood was significantly ($p < .05$) greater than the 96.5 F with the hood.
4. The average heart rate of 90 beats per min. with the hood was significantly lower than the 98 beats per min. without the hood.
5. An average standard deviation of instantaneous heart rate of .027 secs. with the hood was significantly higher than .024 secs. without the hood. The average percent coefficient of variation of heart rate of 4.2% with the hood was significantly higher than the 3.9% without the hood.