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THE CONTROL OF BODY TEMPERATURE IN THERMAL BALANCE

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Physiological responses to changes of environmental temperature or to changes of heat production have been investigated in much detail, but the processes which limit the resulting disturbances of the thermal state are not fully understood. Analogies with industrial and laboratory thermostats have been attempted (Burton, 1941; Glaser, 1953), but such attempts present difficulties because thermostatic design generally aims to keep the temperature of the controlled system as constant as possible, whereas comparatively large variations of the deep and superficial body temperature may be present in man (Pembrey, 1898; Martin, 1930; Horvath & Shelley, 1946; Spealman, 1946). Evidence that heat gains and heat losses can be balanced over a comparatively wide range of deep and superficial temperatures has led to the conclusion that the essential mechanisms of temperature regulation in man are concerned with a constant thermal balance, not a constant deep body temperature (Glaser, 1949, 1953), and experiments have now been carried out in an attempt to find out how thermal balance could be achieved and maintained at different environmental temperatures and after small disturbances of the heat load. Some preliminary findings have already been reported (Glaser & Newling, 1955).

METHODS

Subjects and procedure. Three Chinese men who had lived in Singapore since birth or early childhood took part in the experiment. Their ages were 22–28 years, their heights 163–173 cm and their weights 50·6–60·1 kg. They wore brief cotton shorts only and they lay still on a wheeled stretcher of loosely woven cane throughout each test. All subjects had taken part in similar experiments before, and they had a singular ability to lie still for long periods without any apparent interest in what was going on around them.

Twenty-four tests were conducted, one at a time, in random sequence, and within a total period of 6 months. The subjects always had a light meal first, followed by a period of adjustment which always began between 12.45 and 1 p.m. and during which they lay still in a warm room at

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Singapore room temperature (Table 1). Measurements of the mouth temperature, the skin temperature, the blood pressure and the pulse rate were begun at 2 p.m. and continued at intervals of 10 min, as described below. If all these readings were constant over a period of 10 min to 0·1° C for the mouth temperature, 0·2° C for the skin temperature of the body and limbs, 0·4° C for the skin temperature of the foot, 4 mm of mercury for the blood pressure, and 3 beats/min for the heart rate, it was assumed that the subject was adjusted to the horizontal posture and to the environmental temperature (Table 2).

The subject was then immediately cooled or warmed for exactly 5 min. Cooling was done by covering the fronts and sides of the neck, trunk and limbs (excluding only the head and the soles of the feet) with wet towels, while air movement was increased to 250 m/min by fans placed above the subject and on both sides of him. Measurements of the skin temperature taken towards the end of such cooling showed that the skin was within 0·5° C of the wet-bulb temperature (Table 1). Warming was done by a heating cradle with an inner surface of polished metal fitted with electric light bulbs totalling 1 kW and giving a Globe thermometer reading of 118° C (Bedford, 1948) within the empty cradle. This cradle radiated heat on to the front and sides of the whole body, but not on to the soles of the feet.

TABLE 1. Mean environmental conditions

	Cold room	Cool room	Warm room (Singapore room temp.)	Hot room
Dry-bulb temperature (° C)	17·7	22·9	29·4	39·0
Wet-bulb temperature (° C)	13·4	20·2	24·9	34·2
Vapour pressure (mm Hg)	9·5	16·3	21·5	37·8
Globe thermometer reading (° C)	18·7	23·6	29·4	38·0
Corrected effective temperature (° C) (Bedford, 1948)*	16·5	22·2	26·8	35·2

* The air movement was less than 6 m/min.

After being cooled or warmed for 5 min the subjects either remained at Singapore room temperature, or were immediately wheeled into an adjacent temperature-controlled room which was set at one of three temperatures (Table 1), so that each subject was tested in random sequence in each of four different environments, both after a 5 min period of cooling and after a 5 min period of warming. Measurements of the mouth temperature, skin temperature, blood pressure and heart rate were resumed about 3 min after the end of the 5 min period of cooling or warming and continued at intervals of 10 min until the skin temperatures of the limbs were again constant to 0·4° C, those of the rest of the body to 0·2° C and those of the mouth to 0·1° C.

Environmental conditions are given in Table 1. The air movement was always below 6 m/min except when the subjects were being cooled by wet towels and a fan (see above). During any one test in any one environment the corrected effective temperature never varied by more than 0·5° C and usually by less than 0·3° C. During different tests in the same environment the corrected effective temperature always remained within 1° C of the means given in Table 1, and usually within 0·5° C of those means.

Techniques. The mouth temperature was measured by a thermocouple mounted in the tip of a polythene tube and held firmly under the tongue in the same part of the mouth throughout each test. The mouth temperature was measured in preference to the rectal temperature, because the available evidence suggests either that measurements in these two places are liable to similar errors (Glaser, 1949; Radsma, 1950; Tanner, 1951; Lewis & Renbourn, 1955), or that the mouth temperature is the more accurate index of the deep tissue temperature (Gerbrandy, Snell & Cranston, 1954). The skin temperature was measured in seventeen places, two on the face, five on the chest and abdomen, nine on the limbs including the hand and the upper surface of the foot, and one on the sole of the foot. (It will be remembered that the sole of the foot was not exposed to direct cooling by wet towels or to direct warming under a heating cradle.) The points on the face, the chest and abdomen, and the limbs were so chosen that their means should represent the average temperatures of those areas. These points were also defined beforehand in relation to anatomical markings on the skin, and they were marked by indelible pencil before each test so that there could be no variations between them in any one test and only very small variations in different tests. The temperature of the face, chest and abdomen was measured by a bare thermocouple in a Y-shaped mounting (Glaser, 1949). On the limbs the temperatures were measured by bare thermocouple wires wound around the limb and tightened by a rubber toggle on the opposite side of the limb, so that the junction adhered to the skin at a constant tension without cutting into the skin. All thermocouples were made by welding 32 s.w.g. copper and 36 s.w.g. constantan wires. The skin thermocouples were unlikely to alter the skin temperature even when the latter differed greatly from the air temperature or when the skin was moist (Glaser, 1949). Their design also eliminated errors from variations of pressure at the point of contact, and the thickness of the wires was such that it avoided the disadvantages both of 28 s.w.g. and of 40 s.w.g. thermocouple wires (Stoll & Hardy, 1950). The e.m.f. was read on a Cambridge vernier potentiometer with a Cambridge short-period galvanometer, and the sensitivity of this was so adjusted that a potential difference of 1 μV produced a deflexion of 1 cm on the galvanometer scale. This allowed moderately good readings to 0·01° C and reliable readings to 0·02° C. The standard e.m.f. was obtained from a Weston cell, and a correction was made for environmental temperature. The cold junctions were kept in melting ice insulated by two Dewar flasks, one inside the other, the corks of which were sealed with wax before each test. Calibrations were done in stirred insulated water-baths, using N.P.L. calibrated thermometers for reference.

The blood pressure was measured to the nearest 2 mm by a mercury sphygmomanometer, and auscultation of the brachial artery which had been previously palpated and marked. The precautions taken were those recommended by a committee on Standardization (1939). It was considered best not to record the blood pressure directly, because it was not one of the important readings to be obtained and because indwelling arterial needles would have caused anxiety to the subjects, while the added apparatus would have reduced their mobility and the speed of the experiment (see below). The heart rate was counted over the radial artery during 30 sec using a stop-watch. The environmental conditions were measured every 10 min by an Assmann psychrometer, a Globe thermometer and a very sensitive vane anemometer (Bedford, 1948). The onset of shivering or sweating was determined visually.

Each kind of measurement was always made by the same person, and the record of previous readings was not visible to those taking any particular reading. Measurements were always made in the same order. The thermocouples were so arranged that the mean temperature of nine points on the limbs could be obtained from a single reading. This and rehearsed teamwork between the authors and a technician made it possible to obtain a complete set of observations in 5 min and to keep the time interval between the end of the last preliminary reading and the beginning of the first reading after brief cooling or warming to exactly 15 min.

Statistical calculations. The experiment was so designed that the relation between a number of independent variables was tested in random order. These variables were: (1) four different environmental temperatures, (2) two different previous treatments (pre-cooling and pre-warming), (3) three different subjects. By analysis of variance it was possible, therefore, to assess the effect of any one variable or to estimate the effect of any one variable on either of the other variables. The advantage of such a design was that significant findings were obtained after only three subjects had been tested, while it was possible to find out whether any result was weighted by the responses of any one subject. Since known accidental influences were excluded and unknown ones randomly distributed, it could be assumed that significant results were due to induced changes of environment.

The temperature measurements were in microvolts and all calculations were made on those units of measurement, only the data required for interpretation and publication being subsequently converted to ° C, so that errors of calibration could not have altered the significance of the results. (Over the range considered there is in practice, of course, a linear relationship between e.m.f. and temperature.) Probabilities were obtained from Fisher & Yates's tables (1953).

RESULTS

Observations in thermal balance

Day-to-day variations of the level at which balance was achieved after the initial period of adjustment and immediately before pre-cooling or pre-warming were comparatively large. In spite of carefully controlled experimental conditions their maximum ranges in eight different experiments on any one subject were 1° C for the mouth temperature, 1·7° C for the forehead temperature, 3° C for the foot temperature (Table 2), 26 mm of mercury for the systolic blood pressure, 12 mm of mercury for the diastolic blood pressure, and 10 beats/min for the pulse rate.

There were occasional small differences between successive measurements of the mouth temperature and of the skin temperature when the subjects were accepted to be in thermal balance. Such differences were most marked at 17·7° C, but they were often less than the limits of the techniques employed, and mostly within 0·04° C for the mouth temperature and 0·1° C for the skin temperature (Table 2). The greatest difference of the mouth temperature recorded between successive readings while equilibrium was presumed to exist in any environment was 0·08° C, which is less than the limits set before the experiments (see above). At the same time the blood pressure and pulse rate were frequently constant within the errors of the techniques employed, although in extreme environments, especially when the subjects were shivering, the blood pressure and the pulse rate tended to be less stable than at 22·9° and at 29·4° C.

Effects of environmental temperature

Fig. 1 shows the mean levels of the mouth temperature and of the skin temperature of the sole of the foot when the subjects were in thermal balance in four different environments, and Table 3 shows in more detail the average displacement of the levels of the deep and superficial temperature, the blood pressure and the heart rate under the same conditions. Because of day-to-day variations in the base-line observations (Table 2) the results given in Table 3 were calculated as differences between the means of the last two readings before the 5 min periods of cooling or warming and the means of the last two readings of the same tests when thermal balance had been restored. There was no significant variation between the three subjects of the experiment, apart from the fact that the mean mouth temperature was influenced at the level of $0{\cdot}05 > P > 0{\cdot}02$ by the responses of one subject whose mouth temperature varied less than that of the other two. In spite of this, the mouth temperatures and the skin temperatures of various parts of the body were all positively correlated with the environmental temperature at the level of $P < 0{\cdot}01$, and this correlation was not affected by previous cooling or warming ($P > 0{\cdot}2$).

TABLE 2. Mouth and skin temperatures of subjects in thermal balance at Singapore room temperature (29·4° C)

(Each pair of figures represents two readings at 10 min intervals. All figures are in ° C.)

Subject		At end of preliminary period (8 tests) 1	2	3	4	5	6	7	8	After 5 min cooling	After 5 min warming
A	Mouth	36·54	36·97	36·35	36·65	35·94	36·79	36·72	36·56	36·51	36·86
		36·51	36·97	36·35	36·60	35·92	36·79	36·65	36·51	36·58	36·86
	Forehead	35·83	36·17	36·01	35·90	36·22	36·06	35·86	35·27	35·61	36·08
		35·81	36·22	36·04	35·95	36·22	35·93	35·93	35·02	35·79	36·08
	Sole of foot	33·08	35·56	34·11	35·07	34·62	35·14	35·23	34·80	32·55	35·12
		33·08	35·66	34·11	35·09	34·58	35·12	35·00	34·51	32·14	35·05
B	Mouth	36·37	36·92	36·72	36·44	36·70	36·79	36·84	36·70	36·90	36·30
		36·33	36·90	36·72	36·37	36·70	37·81	36·88	36·70	36·89	36·28
	Forehead	35·29	35·61	35·95	35·68	34·68	36·31	36·08	35·72	35·32	35·36
		35·25	35·70	36·04	35·66	34·56	36·38	36·11	35·74	35·18	35·38
	Sole of foot	31·70	32·19	33·33	33·82	33·72	33·66	33·77	34·68	31·05	33·55
		31·48	32·28	33·55	33·75	33·74	33·37	33·75	34·56	31·12	33·22
C	Mouth	36·90	36·58	36·65	36·44	36·65	36·58	36·60	36·97	36·79	37·04
		36·92	36·63	36·67	36·44	36·67	36·54	36·58	36·97	36·79	37·04
	Forehead	36·58	36·31	36·31	35·81	35·97	35·63	35·90	36·38	36·40	36·78
		36·56	36·33	36·24	35·74	35·83	35·70	35·90	36·35	36·42	36·76
	Sole of foot	35·72	33·93	35·05	32·99	34·68	32·79	33·93	33·91	32·48	35·48
		35·88	34·02	34·82	33·08	34·29	32·90	34·02	33·84	32·41	35·56

TABLE 3. Displacement of the levels at which the mouth and skin temperatures, the blood pressure and the pulse rate achieved balance during exposure to four different environments, both after pre-cooling for 5 min and after pre-warming for 5 min

Mean changes (3 subjects)	Cold room (17·7° C)		Cool room (22·9° C)		Warm room (29·4° C)		Hot room (39° C)	
	Pre-cooling	Pre-warming	Pre-cooling	Pre-warming	Pre-cooling	Pre-warming	Pre-cooling	Pre-warming
Mouth (° C)	−0·68	−0·63	−0·33	−0·31	+0·05	+0·07	+0·40	+0·59
Face (2 points–° C)	−3·85	−4·21	−1·90	−1·46	−0·16	+0·35	+0·87	+1·22
Chest and abdomen (5 points–° C)	−2·61	−3·40	−1·18	−2·68	−0·28	+0·35	+1·39	+1·34
Limbs (9 points–° C)	−7·43	−7·36	−4·30	−3·78	−0·75	+0·14	+1·10	+1·18
Sole of foot (1 point–° C)	−10·51	−10·48	−6·27	−5·85	−1·29	+0·45	+2·16	+3·74
Systolic B.P. (mm Hg)	+14·3	+7·0	+13·0	+2·3	+5·0	+3·3	0	+6·3
Diastolic B.P. (mm Hg)	+18·7	+9·3	+22·7	+10·7	+14·0	−4·0	−2·0	−7·0
Heart rate (beats/min)	+1·3	+5·3	−1·3	+2·7	+0·3	+4·7	+8·3	+16·0
Time needed to reach balance (min)	63	70	50	60	37	33	60	57

The blood pressure tended to be higher at lower skin and mouth temperatures, but it showed no significant correlations with the environment. The heart rate was raised at high environmental temperatures.

All subjects sweated at 39° C and shivered intermittently at 17·7° C. Thermal balance was invariably achieved in the presence of both sweating and shivering, but Table 4 shows that the level of skin and mouth temperature, at which sweating and shivering began, varied during different tests on the same subjects. After pre-cooling all subjects shivered slightly at 22·9° C, but neither the onset nor the cessation of this shivering was related to any definite levels of skin or mouth temperature.

TABLE 4. Temperatures at which shivering and sweating were first observed (° C)

Subject		Mouth	Face (2 points)	Limbs (9 points)	Sole of foot	Time after entering environment (min)
		Shivering in cold room (17·7° C)				
A	Pre-cooling	35·40	31·52	28·32	27·03	50
	Pre-warming	35·18	31·96	28·52	25·16	50
B	Pre-cooling	36·68	33·28	28·76	24·94	50
	Pre-warming	36·77	31·46	29·55	25·12	60
C	Pre-cooling	36·48	31·88	29·25	27·70	5
	Pre-warming	36·85	32·01	30·40	29·40	10
		Sweating in hot room (39·0° C)				
A	Pre-cooling	37·53	36·69	36·50	37·62	50
	Pre-warming	36·83	36·84	35·85	37·16	10
B	Pre-cooling	36·50	35·41	35·02	35·79	10
	Pre-warming	37·03	36·58	34·47	35·43	5
C	Pre-cooling	36·81	36·64	34·81	36·76	20
	Pre-warming	36·70	35·81	34·39	36·26	10

The time required to achieve thermal balance was 30–90 min and this conforms with earlier observations at rest (Glaser, 1949) and during exercise (Martin, 1930). The length of the period of time needed to achieve equilibrium by the criteria given above was related to the environmental disturbance imposed on the subjects, and Table 3 shows that this period was the longest in extreme environments and when previous treatment had the opposite effect to the change of environment.

Effects of short periods of cooling and warming

Fig. 1 and Tables 2 and 3 show that in any one environment the levels at which the temperatures of the mouth and of the extremities achieved balance were higher after 5 min periods of warming than after 5 min periods of cooling, with the exception of the mouth temperature of one subject at room temperature (Table 2). When the effects of pre-cooling and pre-warming were compared in all four environments, none of the differences of the mouth temperatures or of the skin temperatures were significant, but the correlations for the skin temperatures of the sole of the foot approached statistical significance

$(0{\cdot}1 > P > 0{\cdot}05)$. When correlations between the skin temperature and previous cooling or warming were separately calculated for cool and warm environments, disregarding the observations at 17·7° C and at 39° C, a significant correlation was found to exist between the skin temperatures and previous treatment, at the level of $0{\cdot}05 > P > 0{\cdot}01$ for the face and limbs, and at the level of $P < 0{\cdot}01$ for the sole of foot, in spite of the smaller number of observations.

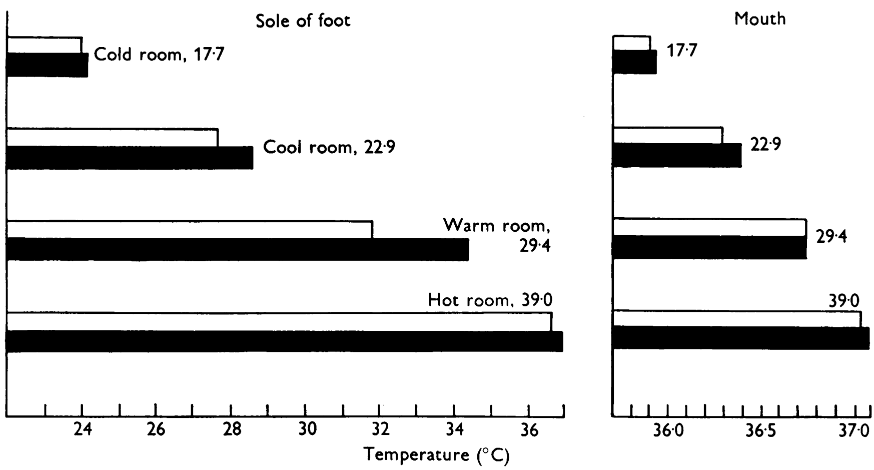

Fig. 1. Mean mouth temperatures and mean skin temperatures of the soles of the feet of three subjects in thermal balance in four different environments after short periods (5 min) of previous cooling by wet towels and fans □, and of previous warming under a heating cradle, ■.

Table 3 shows also that the heart rate was higher in all environments after previous warming than after previous cooling, but this difference only approached the level of significance $(0{\cdot}1 > P > 0{\cdot}05)$. In cool and cold environments the systolic and the diastolic blood pressure rose less after previous warming than after previous cooling. In all environments the diastolic blood pressure was lower after previous warming than after previous cooling, and the latter results were significant at the level $0{\cdot}05 > P > 0{\cdot}01$.

DISCUSSION

The present results show that under physiological conditions the responses following upon a change of heat load are stabilized when heat losses and heat gains are equal and not when the deep or superficial tissues are at any particular temperatures. This confirms that temperature regulation in man is integrated to achieve and maintain thermal balance (Glaser, 1949, 1953). The results also show that thermal equilibrium can be upset by comparatively small disturbances of the superficial temperature, but that the range of body temperatures over which balance can be maintained is wide. From the present results, and from data recorded elsewhere, it may be concluded that variations of the temperature at which thermal balance is possible are of the order of 1° C for the deep tissues and of the order of 10° C for the skin (Pembrey, 1898; Martin, 1930; Nielsen, 1938; Sheard, Williams & Horton, 1941; Horvath & Shelley, 1946; Spealman, 1946; Robinson & Gerking, 1947; Glaser, 1949, 1953). No evidence was obtained of any sensitive mechanisms which limit the range over which thermal balance can be maintained in the zone of temperature regulation by vasomotor control. Changes of body temperature are limited, however, at more extreme temperatures by sweating and shivering, which appear to be superimposed mechanisms and possibly independent from vasomotor control (Table 4).

Day-to-day variations of the deep and superficial temperature which were observed while the subjects remained at rest at Singapore room temperature (Table 2) are unlikely to have been caused by errors of experimental technique, and they suggest the possibility that the level at which the subjects achieved balance after a preliminary period of adjustment on different days may have been influenced by the subjects' previous activities. Moreover, the observations that the level of temperature at which thermal balance was achieved was related to disturbances of the superficial temperature, especially if the subsequent change of environment was not excessive (Table 3, Fig. 1), justify the conclusion that the levels of deep and superficial temperature at which heat losses and heat gains are balanced may depend, among other things, on the previous thermal state. This feature of temperature regulation has some similarity with the findings that posture may be influenced by previous posture (Jackson, 1954) and that responses to cold stimuli may be modified by previous cooling (Glaser & Whittow, 1957). Both the latter findings were claimed to depend on the storage of information by the central nervous system, and it seems possible that such storage plays a part in the modification of thermal equilibria by previous temperatures.

Sweating and shivering

There is some justification for denying that any 'critical' temperatures exist in the control of sweating and shivering (Uprus, Gaylor & Carmichael, 1935; Jung, Doupe & Carmichael, 1937; Glaser, 1949; Glaser & Jones, 1951; Glaser & Lee, 1953; Lee, 1954), and the present results have, again, provided no evidence that the onset of sweating and shivering is related to any particular deep or superficial body temperatures (Table 4). It is probable that the onset of sweating and shivering depends on quantitative thresholds of nervous excitation (Jung *et al.* 1937; Glaser & Jones, 1951; Hensel & Zotterman, 1951; Hensel, 1952; Lee, 1954) in which rates of change (Hensel, 1952), spatial summation (Jung *et al.* 1937) and recruitment (Lee, 1954) all play a part, while the present results have shown that sweating and shivering can be present also during a steady state of thermal balance. The evidence thus allows no precise and positive conclusions about the underlying principles of control.

The blood pressure and heart rate

The subjects were physically and mentally at rest during the present experiments, so that variations of the blood pressure and heart rate must have been largely a result of heat-regulating responses. Indeed, the fact that short periods of cooling raised the level at which the blood pressure achieved equilibrium and lowered the level at which the heart rate became constant, while short periods of warming had the opposite effect, suggests that physiological variations of the blood pressure and of the heart rate may be caused, among other things, by physiological fluctuations of the level of thermal balance. The heart rate may also vary, however, as a result of direct effects of temperature on the nervous mechanisms controlling the heart beat (Tanner, 1951; Cooper & Kerslake, 1955) and for this reason variations of the heart rate can sometimes be true heat-regulating responses.

Practical considerations

The present investigation suggests that disturbances of the thermal state could be used to practical advantage. For example, people living in a warm climate who cannot sleep or cannot concentrate on their work because they feel too hot might lower their skin temperature to a more comfortable level by a cold bath, and they might maintain such a level while they remained at rest. People at rest in a cool place could similarly benefit from short periods of warming. Such transient cooling or warming would probably be more effective if thermal discomfort was partly or wholly due to a previous thermal disturbance, but it would be ineffective in extreme environmental conditions (Fig. 1, Table 3).

SUMMARY

1. Three men at rest were exposed to four different environments after periods of controlled cooling or warming lasting 5 min.

2. When the subjects were in thermal balance the deep and superficial temperature was correlated with the environmental temperature, and it was confirmed that the maintenance of thermal balance is a fundamental property of temperature control in man, while the deep and superficial temperature may vary within fairly wide limits.

3. Short periods of previous cooling caused a reduction and short periods of previous warming caused an increase of the level of skin and mouth temperature at which thermal balance was achieved in any one environment. This was significant with regard to the skin temperature of the face and of the

extremities and within the zone of temperature regulation by vasomotor control, and it implies that the level at which thermal balance is achieved may depend, among other things, on the previous thermal state.

4. When thermal equilibrium was upset, the time required to restore it was related to the magnitude of the disturbance.

5. Under physiological conditions fluctuations of the level over which thermal balance could be maintained were effectively limited by sweating and shivering.

6. Physiological variations of the blood pressure and the heart rate at rest appear to have been caused, among other things, by changes of the temperature at which heat losses and heat gains were balanced.

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