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Physical Performance in Relation to External Temperature.

By

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With 4 Figures.

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Man's response to an increase in external temperature is familiar enough in certain respects. In rest, the heat control mechanism together with voluntary actions may maintain a constant internal temperature. If external temperature and humidity are sufficiently high, body temperature increases and then physiological responses may be quantitatively or even qualitatively different; eventually the phenomena of heat stroke are observed. In exercise, the increased rate of heat production calls for a corresponding increase in rate of heat dissipation; if these rates are not equal body temperature changes. The rate of heat dissipation depends on various internal conditions, such as the rate of heat production and the rate of blood movement from active muscles to the periphery, as well as on such external conditions as temperature, relative humidity and velocity of air movement. The problem of temperature control in exercise is so complex that relatively few studies have yielded useful quantitative results.

The numerous precautions which must be taken if one is to establish a precise relation between temperature and various physiological functions have been worked out for various species of animals by *Crozier* and associates. Reference may be made, for example, to *Crozier* and *Stier*[1]. It is impossible when man is the subject to attain such constancy of conditions. What we have done consists of a study of performance with approximately constant humidity (50 per cent), with almost no air movement and with the room temperature either at 12 ± 1 °C or at 34 ± 1 °C. Internal conditions could not be controlled so precisely. Each of the 5 subjects worked in the hot room at a rate which brought on exhaustion in from 37 minutes to an hour and at the same rate in the cold room. We propose to present and discuss both the uniformities and the differences of response of the 5 individuals to these different working conditions.

The experimental methods used, with a few exceptions, have been described before[2]. The bicycle ergometer is provided with a speedometer recording distance and showing rate. The brake band passes under the fly-wheel and is supported by adjustable sensitive spring balances which are suspended vertically. The adjustment of the balances must be made frequently during an experiment in order to maintain constancy of load. By regular observation of the clock, speedometer and time-table, the subject soon learns to adjust his rate at about 65 r. p. m., — the optimum established by *Dickinson*[3]. There are minute-to-minute variations but these disappear when 5-minute intervals are compared.

We had to consider the possibility that extraneous frictional losses might vary significantly over the temperature range studied. An investigation of this subject proved that the energy requirement for maintaining a rate of 65 r. p. m. with no load was about 400 kg/m. per hour in the hot room and 800 kg/m. per hour in the cold room*. Since the difference, 400 kg/m. per hour, is only about one percent of the rate of work in our experiments, the correction is negligible, or nearly so. The net effect of the correction would be to increase the mechanical efficiency in the cold room by 0.2 %.

Rectal temperature was determined by use of a two-junction thermocouple, constructed of copper and of constantin wire 0.1 mm in diameter. The hot junctions are sealed in a silver tube 10 mm long and 2 mm in outside diameter. The cold junctions are kept in a Dewar flask containing a water-ice mixture. The wires are sealed in a rubber tube 3 mm in outside diameter. With this type of construction thermal equilibrium is attained in about 2 seconds. Potential difference is determined by use of a Leeds and Northrup Potentiometer, Type K, using a Leeds and Northrup Galvanometer, Type R. Frequent checking against a Bureau of Standards thermometer indicates that all the temperature values are accurate within 0,1 °C and most of them within 0,02 °C.

The heart rate was determined by a modification of the cardiotachometer described by *Boas*[4]. The essential feature of our instrument is the use of a highly resonant amplifier with proper shielding which permits complete freedom of movement on the part of the subject and eliminates the effect of static and low frequency potentials associated with muscular movements or with contact with the observers.

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* The extraneous frictional losses were evaluated by determining the negative acceleration of the ergometer running with no load at the angular velocity used in these experiments. On the assumption that the kinetic energy of the system is a function of the angular momentum of the 23 kg. fly-wheel, one can easily calculate the energy equivalent of frictional losses.

The subjects studied varied in working capacity, as may be seen by reference to Table 1. J. S. (wt., 77 kg; ht., 180 cm; age, 43) is an oarsman of many years' experience and was in active training at the time of these experiments. R. S. N. (wt., 77 kg; ht., 177 cm; age, 22) is a student without training in athletics but with much experience as a subject. D. B. D. (wt., 75 kg; ht., 179 cm; age, 39) and W. C. (wt., 64 kg; ht., 170 cm; age, 20) have frequently acted as subjects. D. F. C. (wt., 65 kg, ht., 170 cm; age, 35) is a sedentary worker with a few weeks' experience as a subject.

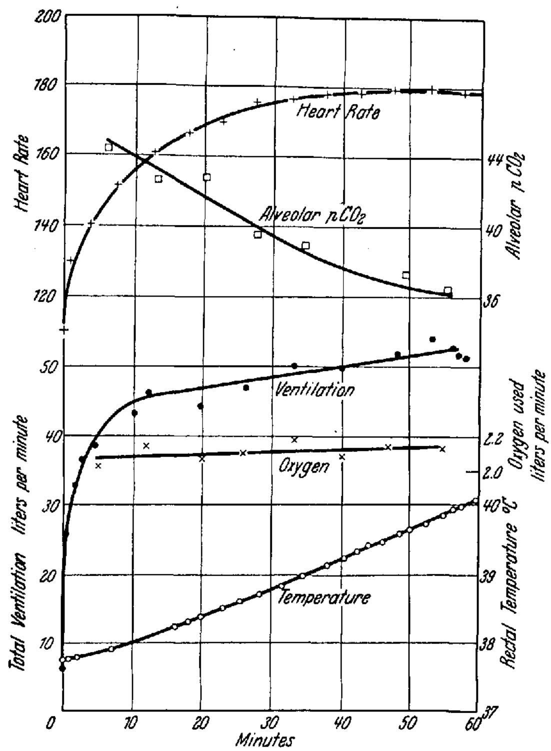

Fig. 1.

Since it is out of the question to give in detail the protocols of the experiments, Fig. 1 has been prepared to illustrate some of the changes observed in the course of a single experiment. This experiment on J. S. in the hot room is of interest for the reason that rectal temperature increased in a linear fashion and reached a final value of 40,1° C, the highest observed in any subject. Since work was being done at a constant rate, we are able, in this case, to estimate the influence of a considerable change in body temperature upon various physiological functions.

It will be noted (Fig. 1) that the rate of oxygen intake was nearly constant after the fifth minute. From that time on there may have been a further increase not exceeding 5 per cent although the fluctuation is great enough to render this conclusion uncertain. It follows that as body temperature increased from 38 to 40° the efficiency with which work was performed may have decreased slightly but certainly did not decrease more than one-twentieth. The results on other individuals were of a similar character; no subject showed a large change in efficiency when external conditions were such as to cause a steady increase in body temperature.

The total volume of air breathed increased throughout this experiment, the final rate being one-sixth greater than the rate after 10 minutes' work. Together with this increase there was an associated decrease in alveolar carbon dioxide pressure. Increase in temperature increases the base-binding capacity of body proteins at a given hydrogen ion concentration. In order to maintain a constant hydrogen ion concentration while body temperature is rising, carbon dioxide must be liberated by the lungs faster than its rate of production by oxidative processes. However in our experiments the level of oxidative processes was so high that the excess CO_2 given off from body stores is relatively unimportant. A rough calculation indicates that from 20 to 30 ccm per minute may have been given off by temperature effect on base-binding capacity of proteins. In this same experiment change in alveolar carbon dioxide pressure from 44 to 36 mm corresponds to about the same rate of excess CO_2 output. These two changes together would modify the respiratory quotient (R. Q.) by about 0.02. The net result of these changes of temperature, of breathing and of the slight increase in lactic acid (Table 1) is an increase in p_H of arterial serum from 7.36 to 7.37, that is, the reaction remains constant or nearly so.

Fig. 1 also shows the heart rate throughout the same experiment. This is an unusual record in that this subject was the only one able to maintain a rate of 178 to 180 for 20 minutes. A more typical record of heart rate is that of W. C., shown in Fig. 2. This subject became exhausted in the hot room when his heart rate (continuous line) reached 180 while in the cold room, work was continued the full hour without exhaustion;—the heart rate (broken line) did not exceed 135. Rectal temperatures for the same two experiments on W. C. are shown in Fig. 3. These curves are typical, *viz.*, there is usually an increase at the beginning of work and then a steady state if external temperature is low.

These observations on W. C. have been used in Fig. 4 to show the relation between temperature and heart rate in exercise. There is first of all a considerable increase in rate early in the experiment which is nearly independent of temperature, external or internal. In the cold room an equilibrium heart rate is reached which is modified only slightly

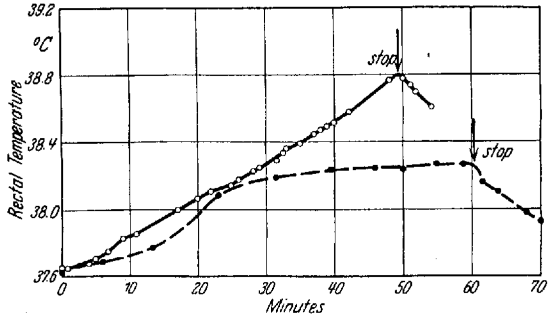

Fig. 2.

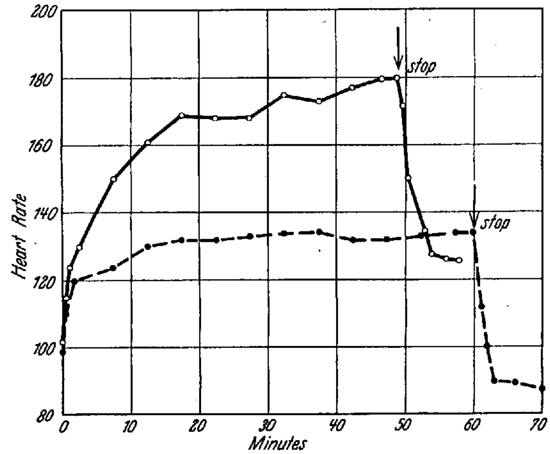

Fig. 3.

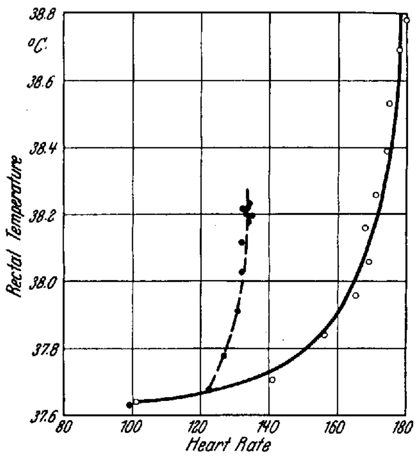

Fig. 4.

by further increase in internal temperature. Comparison of the two curves shows a great difference in rate when internal temperature is the same but external temperature different. These observations are in harmony with those of *Hill* and *Campbell*[5].

The summarized results of 10 experiments such as those discussed above are presented in Table 1. Considering first of all the efficiency with which work is performed, it is evident that the differences between hot and cold room experiments are negligible. These values are similar to those found at intermediate remperatures by *Benedict* and *Cathcart*[6]. It is probable, therefore, that in heavy muscular work which does not require much nervous coordination and with other experimental conditions as described, the mechanical efficiency does not vary significantly with temperature between the limits 12° and 34°C. This question has been studied by *Ohnishi*[7] who found that there is little variation in mechanical efficiency with temperature. Mean values for efficiency at 10, 20, 30 and 40°C were 15.0, 15.6, 17.8 and 15.6 per cent, respectively. *Hill* and *Campbell*[5] have reached a similar conclusion. It is quite possible that in such forms of activity as walking or running one might find large variations in oxygen intake with variation in external and internal temperature. In such activities skill is an important factor[2]; in riding the ergometer it is nearly negligible as is proved by the uniformity in efficiency of our 5 subjects.

The fuels used are not significantly different in the two environments. If one takes into account the excess CO_2 given off in the hot room as suggested above, the corrected R. Q. values would be even less divergent than those given in the table. Since the experiments were carried on from 2 to 3 hours after a meal, higher quotients were found than one finds during similar exercise in a post-absorptive state. The respiratory quotient remained above 0.9 in every experiment and since the same oxygen intake was maintained in the hot and cold room experiments, it follows that exhaustion could not have been related to depletion of fuel reserves. Furthermore, observations on blood sugar at the conclusion of work gave values within the normal range in all cases.

The literature on the subject of rectal temperature during exercise has been reviewed by *Christensen*[8]. His experiments have been carried out with an external temperature of 19 to 21° and with rapid air movement. The rate of work varied from 720 to 1920 kg/m per minute, i. e., the minimum was of the same order of magnitude as the rates used in our experiments. The temperature curves he has obtained are similar in character to ours with but one exception; he has commonly observed a decrease in temperature during the first 2 or 3 minutes of work. In our experiments there is sometimes a lag of 2 or 3 minutes before temperature begins to increase but a decrease during this period is never observed.

The rectal temperatures reached in our experiments indicate that exhaustion in the hot room was not due simply to an uncomfortably high temperature. Thus 3 subjects had a temperature only 0.5° higher in the hot room than in the cold room. Temperatures of 40° are not uncommon in an athlete and even 40.6 has been observed by *Hill* and *Flack*[9]. Under conditions quite unfavorable for heat dissipation and with a moderate rate of oxygen intake we have found that even the non-athlete can attain a temperature 39 to 39.5° before he becomes exhausted.

The figures given for lactic acid concentration indicate that exhaustion was not due to accumulation of acid in the body as a whole. The limiting concentration for lactic acid in short periods of work to exhaustion is usually 8 to 10 mEq. per liter. The highest observed in these experiments was 5,4 and R. S. N. had only 3,1 when exhausted. This implies that the oxygen supply to the main mass of active muscles was adequate (*vide infra*). It does not follow that oxygen supply to the heart was adequate. It is possible that when exhaustion comes, the lactic acid concentration in heart muscle has reached a higher value than that observed in venous blood drawn from the arm. The heart is such a small fraction of the total muscular tissue that a high lactic acid concentration in it alone would not result in much increase in the body as a whole.

As judged by output of blood per unit time and systolic pressure, the mechanical work done by the heart per unit time was about the same in the hot as in the cold room. The circulation rate as determined by the carbon dioxide method (which may give incorrect absolute values but probably reveals change in rate) seemed to be either the same or slightly greater in the hot room. The systolic pressure during work in the hot room was the same in some subjects and somewhat less in others. There is an indeterminate error in judging rate of work output on such a basis since the character of the dependence of pressure and volume on time is not known. The heart rate was always higher in the hot room and the mechanical efficiency of the heart probably was less. If these assumptions are correct, its oxygen requirement per unit time is greater in the hot room.

The distribution of blood in exercise clearly depends upon temperature. Blood supply to the skin is increased with increase of external temperature. There may be noticeable edema on the hands, skin temperature may nearly reach body temperature (see *Ohnishi, loc. cit.*) and the rate of sweat excretion may be increased to 2 kg per hour. Observations on the oxygen content of blood from the ante-cubital vein, given in Table 2, have a direct bearing on this question. The calculations given in this table are not precise for one does not know the relative oxygen consumption of the cutaneous and subcutaneous tissues but a general qualitative idea is gained of change in blood supply to these tissues with change of external temperature. One can safely assume that neither tissue has a lower oxygen requirement in the hot room than in the cold room; accordingly the ratios given in Table 2 are more probably too small than too large.

Since there is no direct measure of the distribution of blood between active and inactive tissues, it is impossible to estimate directly the effects of slightly increased total cardiac output and considerably increased blood supply to the skin and idle tissues upon blood supply to active muscles. It has been shown[10] that during work of a given intensity a decreased partial pressure of oxygen results in a higher equilibrium level of lactic acid. It is probable, therefore, that the greater concentration of lactic acid observed in our hot room experiments, particularly in the less powerful subjects, is due to a lower partial pressure of oxygen in capillaries of active tissues, i. e., it reflects a decreased rate of blood supply to the active tissues. A steady state may be attained since accumulation of lactic acid helps to turn out oxygen from the blood to the tissues*.

In seeking for the cause of exhaustion we are left by a process of elimination with the possibility that the heart muscle itself was exhausted. The evidence for this is indirect and therefore inconclusive. There is, in the first place, the fact that in every case the heart rate had reached its upper limit when exhaustion occurred while every other function which could be measured had ample reserve. The outcome of many hot-room experiments such as those summarized in Table 1 is the same, *viz.*, the maximum heart rate is reached simultaneously with the onset of exhaustion. Only an athlete such as J. S. continues working at a high temperature after his maximum heart rate is attained. Secondly, there is the evidence of a decreased blood supply to active muscles when work is done at a high external temperature. Skeletal muscles are not called upon for more work and may reach an equilibrium with regards to oxygen supply by a slight further increase in lactic acid accumulation. The heart, on the other hand, beats faster, presumably is less efficient, and hence requires more oxygen at a time when its blood supply may actually be

* An alternative explanation of the higher lactic acid concentration observed in the hot room experiments has been suggested by Professor *E. G. Martin* (personal communication). It is possible that the supply of blood and of oxygen to active muscles is the same in the two environments and that the increased rate of blood supply to the skin is at the expense of blood-flow through the liver. Since the liver may have an important function in lactic acid resynthesis in exercise as suggested by *Himwich, Koskoff* and *Nahum*[11], a higher lactic acid level in the body as a whole might be a consequence of diversion of blood from the portal circulation. However in work of this intensity the hypothesis that the liver has an important role in resynthesis of lactic acid implies an excessively large supply of blood to it at a time when it is imperative that the muscles have a large supply also.

Table 1. *Performance in Relation to Room Temperature.*
Temperature of hot room 34±1°; of cold room, 12±1°. Relative humidity about 50%.

Subject	J. S.	R. S. N.	D. B. D.	W. C.	D. F. C.
Duration of expt., min.*	60	40	40	49	37
Oxygen used, *l. per min.*					
(a) Hot room	2.10	2.22	1.88	1.70	1.46
(b) Cold room	2.21	2.34	1.81	1.68	1.39
△	+0,11	+0.12	−0.07	−0.02	−0.07
Work, *kg/m per hr.* $\times 10^{-3}$					
(a)	48	48	43	36	31
(b)	49	48	42	36	30
△	+1	0	−1	0	−1
Mechanical efficiency, *per cent*					
(a)	20.5	19.5	20.5	19.7	19.6
(b)	20.1	18.6	20.8	19.6	20.0
△	−0.4	−0.9	+0.3	−0.1	+0.4
R. Q.					
(a)	0.95	0.97	0.96	0.94	0.98
(b)	0.93	0.97	0.95	0.93	0.96
△	−0.02	0.00	−0.01	−0.01	−0.02
Final rectal temp., °C.					
(a)	40.08	39.13	38.80	38.78	38.12
(b)	38.47	38.26	38.42	38.22	37.65
△	−1.61	−0.87	−0.38	−0.56	−0.47
Final heart rate					
(a)	179	177	162	180	177
(b)	150	157	136	132	122
△	−29	−20	−26	−48	−55
Arterial blood pressure, *mm Hg.*					
(a)	189	185	156	136	121
(b)	222	199	156	146	122
△	+33	+14	0	+10	+1
Cardiac output, *l. per min.*					
(a)	20	20	24	18	21
(b)	20	19	22	16	17
△	0	−1	−2	−2	−4
Final lactic acid concentration in venous blood, *mEq per l.*					
(a)	3.7	3.1	5.4	5.0	3.8
(b)	2.7	2.6	2.1	1.4	1.5
△	−1.0	−0.5	−3.5	−3.6	−2.3

* The experiments in the hot room terminated with exhaustion at the time indicated. Those in the cold room lasted for 60 minutes but the values given in the table cover the period coextensive with the corresponding hot-room experiment.

decreasing because of decreasing systolic pressure. The hypothesis is advanced that exhaustion comes when the accumulation of lactic acid in the heart has reached a limiting value.

Table 2. *Oxygen Transport to Skin and Idle Tissues.*

Subject	J. S.		R. S. N.	
	Hot Room	Cold Room	Hot Room	Cold Room
Oxygen in venous blood, *per cent of capacity**	89.7	66.0	89.0	32.0
Oxygen transport, *per cent of capacity*	5.3	29.0	6.0	63.0
Ratio of oxygen transport, Cold room : Hot room	5.5		10.5	

Summary

The effects of external temperature on performance have been studied in the case of several individuals. Each subject did the same work on the bicycle ergometer with (a) an external temperature of 12 ± 1 °C and (b) an external temperature of 34 ± 1 °C and a relative humidity of about 50 % in each case. The work done involved an oxygen consumption of 1,9 ± 0.5 liters per minute and a moderate or small oxygen debt. Rectal temperature was observed frequently, using a thermocouple, and heart rate was recorded continuously with a cardiotachometer. Observations on the metabolism indicated that work is carried on with the same mechanical efficiency and with the same fuels under these extreme conditions (Table 1).

For a given rate of work the rate of increase of body temperature as work is carried on is nearly constant for the first few minutes (Fig. 3). Then a constant temperature may be reached if conditions for heat dissipation are favorable; otherwise body temperature rises until exhaustion intervenes.

The heart rate increases with external temperature even when internal temperature is the same (Fig. 4). Its output per unit time may remain constant or increase slightly. Consequently its output per beat must diminish with increasing external temperature. Blood supply to the skin and inactive muscles increases (Table 2) and to active muscles probably diminishes with increasing external temperature.

In our experiments 4 of the 5 subjects became exhausted at the high temperature when doing work which they carried on easily at a low temperature. Yet there was no considerable lactic acid accumulation in the body as a whole, no exhaustion of fuel reserves, and a large unused

* The assumption is made that arterial blood is 95 per cent saturated with oxygen in each case.

reserve of pulmonary ventilation. The most probable hypothesis for explaining these data is that the heart muscle itself had reached the limit of its capacity, for it had attained its maximum rate while no other part of the organism was working at capacity.

The implications of these experiments are many, for physical activity is often carried on under conditions unfavorable to heat dissipation. The leisurely habits of those who live in the tropics have a sound basis in physiological necessity.

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