J. Physiol. (1956) 132, 559–576

NATURAL AND ARTIFICIAL ACCLIMATIZATION TO HOT ENVIRONMENTS

By R. F. HELLON, R. M. JONES, R. K. MACPHERSON AND J. S. WEINER

From the Medical Research Council's Unit for Research on Climate and Working Efficiency, Oxford, and the Royal Naval Tropical Research Unit, University of Malaya, Singapore

(*Received* 24 *January* 1956)

If men without previous experience of hot environments are repeatedly exposed to such conditions in laboratory climatic chambers or hot rooms, their physiological response to these conditions is rapidly modified. The changes most easily and regularly observed are a progressive reduction in the increments in the skin and deep body temperature, and in the heart rate, produced by exposure to a standard environment, accompanied by a speeding up of the onset of sweating, and an increase in the amount of sweat lost (Bean & Eichna, 1943; Ladell, 1947; Robinson, Turrell, Belding & Horvath, 1943). There is a concomitant improvement in the subject's ability to perform muscular work, and a noticeable reduction in his feelings of discomfort.

The term 'artificial acclimatization' is generally used to describe these changes seen in the laboratory, because it has been assumed that they constitute, or form part of, the adaptation to high environmental temperatures that occurs naturally in newcomers to hot climates, and results in an increased ability to work in the new environment and a reduction in the discomfort experienced. This assumption is implicit in most of the laboratory work done on the effects of hot environments: but, as far as is known, it has never been rigidly demonstrated because of the technical difficulties involved.

Experiments conducted at Singapore to determine the responses to a variety of hot environments of men naturally acclimatized to tropical conditions, in order to compare their response with that of men artificially acclimatized to heat in laboratories in temperate climates, had proved unsatisfactory because repeated exposure of the subjects in the hot room produced a progressive change in their behaviour. It was, therefore, decided to use a large group of men, and expose each man twice only, with a standard interval between the two exposures. On the first occasion all men would be treated alike in a dummy experiment or 'uniformity trial', and the results of this experiment used to correct for differences between individuals when, on the second occasion, small groups were exposed to the various hot environments, the effects of which it was desired to determine. It was considered that by these means an accurate determination could be made of the response to hot environments of these men in their natural state of acclimatization. This proved to be so, and the results of this series of experiments have already been described (Adam, Jack, John, Macpherson, Newling & You, 1953).

It occurred to one of us (J. S. W.) to perform an exactly similar experiment in England on another group of men, identical in all respects with the first group, except that the second group had not been exposed to hot environments, either naturally or in the laboratory. A comparison of the results from the two groups of subjects could be expected, not only to provide a measure of the difference between the heat tolerance of men resident in England and that of a similar group resident in Singapore, but also to demonstrate whether the physiological changes seen in artificial conditions were evinced also by Europeans in the ordinary course of residence in tropical climates.

The difficulty in comparing two such groups of men is to ensure that both groups can be regarded as valid samples of the same population. In this case the difficulty was largely overcome by the fact that naval ratings were used in the experiments in Singapore and, by the co-operation of the Royal Navy, it was possible to select a comparable group from among volunteers in this country.

METHODS

Plan of experiment

In the first test all the subjects received exactly the same treatment—they performed a standard task in a standard environment (dry-bulb 100° F, wet-bulb 85·5° F, air speed 100 ft./min), they all wore shorts, and the test in all cases lasted for 4 hr. The standard task consisted of alternate periods of step-climbing on stools 12 in. high 12 times per min, and resting seated on the same stools (see Table 1). The rate of energy expenditure while step-climbing was 170 kcal/m²/hr, and while sitting 55 kcal/m²/hr, and the mean rate of energy expenditure was 106 kcal/m²/hr. Three days after this uniformity trial each man underwent the second test. The conditions in this test were arranged in accordance with a factorial design involving four factors, dry-bulb temperature (D), wet-bulb temperature (W), air speed (A), and activity (P), each at two levels—D_1 90° F, D_2 120° F; W_1 80° F, W_2 85° F; A_1 20 ft./min, A_2 300 ft./min; P_1 'sitting' and P_2 'working'. The men wore shorts only. At the lower level of activity, P_1 ('sitting'), the men remained seated on their stools for the whole of the experiment. Their energy expenditure was therefore 55 kcal/m²/hr. At the higher level of activity, P_2 ('working'), the men followed the same routine of alternate resting and step-climbing as in the uniformity trials (see Table 1). The average energy expenditure was therefore 106 kcal/m²/hr. There were thus sixteen treatments, each of which was undergone by two subjects. The order in which the treatments were given was allocated at random and the men were chosen for sitting and working by lot.

The arrangements at Oxford followed closely those at Singapore (Adam, Jack *et al.* 1953). On the evening of day 1 two men reported at the Climatic Unit at Oxford, where they spent the night under supervision. The next morning, day 2, they were medically examined and were instructed in the procedure of the tests, and that afternoon they underwent the uniformity trial. Two more men reported on the evening of day 2, slept the night at Oxford, and on day 3 underwent the medical examination, and in the afternoon the uniformity trial. On day 4 the first two men reported again, spent the night at Oxford, and next morning, day 5, carried out the test allotted to them in the 'factorial experiment'. This second exposure to heat was thus experienced 3 days, less 4 hr, after the uniformity trial. The second pair reported at Oxford on the evening of day 5, and next morning, Day 6, underwent their allocated heat test, again 3 days less 4 hr after their first exposure, and so on for the remainder of the thirty-two subjects.

TABLE 1. Experimental routine used at Singapore

Time (min)	
-20	Rest outside climatic chamber
-5	Pulse rate; rectal temperature
0	Enter chamber; weighed nude; don clothing; sit on stool
5	Skin temperatures
10- 40	'Work I'*
40	Measurements; drink 500 ml. water
50- 60	Rest seated
60	Measurements
70–100	'Work II'*
100	Measurements; drink 500 ml. water
110–120	Rest seated
120	Measurements
130–160	'Work III'*
160	Measurements; drink 500 ml. water
170–185	Rest seated
185	Measurements
195–210	Rest seated
210	Measurements
220–240	'Work IV'*
240	Measurements; leave chamber

* During these periods the subjects remained seated (the lower level of activity, P_1) or step-climbed on their stools (12 in. high) 12 times per min (the higher level of activity P_2, and all subjects in the uniformity trials).

Measurements: Pulse rate; skin temperatures; rectal temperature; weighed nude.

Hot-room procedure

The hot-room procedure followed in Singapore is set out in Table 1. There was one minor departure from this routine at Oxford. No observations were made at 185 min during the hour's rest after the third work period. One other modification was also introduced. The subjects sat or step-climbed on towels in order to collect the sweat lost by dripping, and these towels as well as the men's shorts were weighed on every occasion when the man himself was weighed.

Particulars of the subjects

Every effort was made to obtain naval ratings of age, height and weight similar to those at Singapore, with the essential qualification that none of the men had ever served in tropical climates or worked in hot spaces, e.g. boiler rooms and engine rooms in ships.

In certain respects the men did not completely match the Singapore group. Volunteers for the experiment from the different establishments were not plentiful enough to restrict the choice to able-bodied and ordinary seamen as was done at Singapore, and only nine men fell into these two categories. However, in the case of a further fifteen subjects the occupations followed did not require work in hot surroundings. These fifteen comprised eleven marines, three fleet-air-arm personnel and one sick-berth attendant. The remaining eight required to make up the quota of thirty-two were stoker mechanics, but five of these were new entrants without any service in the engine room, two others had each had a few weeks' engine-room experience during their training, some 3 months previous to the present investigation, but without experiencing particularly warm conditions. The eighth man had served 6 months in the engine room some 2 years previously. Only four of the thirty-two men, including three experienced stoker mechanics, had been out of the country, and these had been stationed at Gibraltar 17 months previously or more. The group can therefore be accepted as comprising men with virtually no experience in hot conditions and certainly with no experience of the tropics. In contrast, the Singapore subjects had lived in the tropics for periods ranging from 7 to 23 months, with an average of 17·6 months at the time of the tests.

Age and physical characteristics. For comparison with the Singapore series, the mean age, weight, height and surface area, with their standard deviations, of both groups of subjects are given in Table 2.

TABLE 2. Physical characteristics of subjects at Oxford and Singapore—mean values and standard deviations

	Mean value		Standard deviation	
	Oxford	Singapore	Oxford	Singapore
Age (years)	20·17	20·92	1·84	2·19
Weight (kg)	65·591	65·575	7·245	6·05
Height (cm)	172·56	171·97	5·137	3·73
Surface area (m^2)	1·770	1·773	0·1154	0·09

The age range of the Oxford subjects, 17–27 years, was the same as that of the Singapore group. Their mean age, however, was 9 months less, and the distribution of ages was somewhat different. Eleven of the thirty-two Oxford subjects were below 19 years, and seventeen below 20 years of age, as compared with two and seven respectively at Singapore, though all but four at Oxford and five at Singapore were between 17 and 22 years of age. In respect of age therefore, the two groups, though not very dissimilar, cannot be regarded as samples drawn from the same population. The difference between them is formally just significant at the 5% level.

The mean and the distribution of weight, height and surface area of the two groups were very similar, and in these characters the groups may be held to represent two random samples taken from the same population. The small difference of age distribution was therefore not reflected in any difference in the physical characteristics of the two groups.

The uniformity trial provides a direct comparison between the tropical and non-tropical subjects, utilizing all sixty-four men of the two groups, all tested in one set of conditions. The factorial experiment allows comparisons to be made between the groups for sixteen additional sets of conditions, but here only two men in each group are available. Individual variability must obviously affect such comparisons, but corrections on this score can be applied and this has been done by using the method of analysis of covariance as explained on p. 565.

RESULTS

Uniformity trials

Total sweat loss. The mean values for the two groups (Table 3) show that the Oxford subjects sweated much less than did those at Singapore. The difference between the means is highly significant ($P < 0·001$).

It is well known that sweat output is affected by body size (Adam, Jack *et al.* 1953). The correlation coefficients of sweat loss on body weight for the Singapore and Oxford groups are 0·764 and 0·732, which are not significantly different, and for the groups together, 0·745. The increase in sweat loss with body weight of the two groups is given by the mean regression coefficient $b = 27·54$ (S.E. 3·15) g/kg, which represents the slope of the best fitting pair of parallel regression lines. Thus the sweat loss at Oxford and Singapore may be represented by the two regression equations

$$\text{Singapore} \quad y = 374 + 27{\cdot}54x,$$
$$\text{Oxford} \quad y = -107 + 27{\cdot}54x,$$

where y is the total sweat loss in 4 hr in grams, and x is the body weight in kilograms. The difference between the groups is again very clear.

It has been pointed out that the two groups of subjects differed somewhat in their age and distribution. This difference, however, plays no part in the sweat responses of the subjects, for there is no discernible relation between sweat loss and age over the range covered by these subjects. Neither the correlation coefficient $-0{\cdot}021$, nor the mean regression coefficient $b = -2{\cdot}6 \pm 15{\cdot}6$ g/yr, is significant.

TABLE 3. Total sweat loss in uniformity trials (g/4 hr)

	Oxford	Singapore
Mean value	1699	2180
Standard deviation	266	226
Standard error	47	40

Rectal temperature. The results are summarized in Table 4 and Fig. 1, which give the rectal temperatures taken before and throughout the whole exposure of 4 hr. The mean initial values at Singapore and Oxford were 99·64 and 99·48° F, but the difference $0{\cdot}16 \pm 0{\cdot}104°$ F is not significant; the Oxford subjects appear slightly more variable, but the difference between the variances is not significant. During the trials the Oxford values after the first hour are consistently higher though more variable than those at Singapore. The difference amounts to nearly 1° F towards the end of the experiment. By the end of the second and third work period, the Oxford values have risen 1·85 and 1·97° F compared with 1·12 and 0·87° F for Singapore. The Singapore values after a peak at the end of the first work period begin to fall; at Oxford, there is a further rise until the end of the third work period. The median values are included in the table to show that high Oxford rectal temperatures cannot be attributed to one or two exceptional subjects.

Skin temperature. The findings are shown in Table 5 and Fig. 2. Initially, the mean temperatures at Oxford, like the rectal temperatures, were slightly lower than those at Singapore. After the first work period, however, and during the remainder of the trial, the Oxford values were the higher. There is one further striking contrast—during the work periods at Oxford skin temperatures rose, while at Singapore they fell. This phenomenon has been discussed at length by Ferres, Fox, Jack, John, Lind, Macpherson & Newling (1954).

Standing pulse rate. The mean values for the standing pulse rates throughout the experiment for both the Oxford and Singapore subjects are set out in Table 6 and Fig. 3. Before entering the hot room there is no significant difference between the tropical and the Oxford subjects, but from the end of the first work period onwards the values for the Oxford subjects are considerably higher than those for the Singapore subjects.

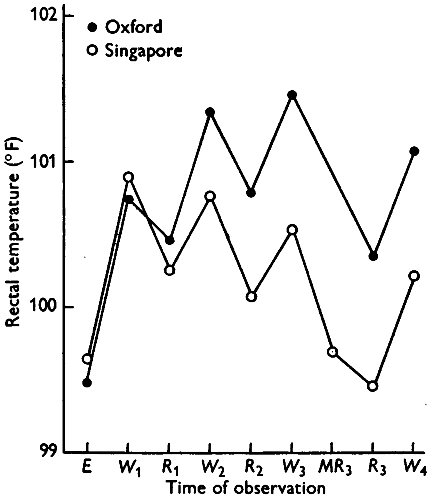

Fig. 1. Rectal temperatures (° F) during uniformity trials at Oxford and Singapore. *E*, before entry; *W*, end of work period; *R*, end of rest period; MR_3, middle of third rest period (Singapore only).

Table 4. Rectal temperatures during uniformity trials (° F)

	Mean		Variance*		S.E. of mean		Median	
	O.	S.	O.	S.	O.	S.	O.	S.
Before entry	99·48	99·64	0·223	0·125	0·084	0·062	99·5	99·7
End of work I	100·73	100·89	0·224	0·129	0·084	0·064	100·8	100·9
End of rest I	100·46	100·25	0·182	0·197	0·075	0·078	100·5	100·3
End of work II	101·33	100·76	0·540	0·160	0·130	0·071	101·4	100·7
End of rest II	100·78	100·07	0·801	0·154	0·158	0·070	100·8	100·0
End of work III	101·45	100·53	0·917	0·130	0·169	0·064	101·45	100·55
End of rest III	100·35	99·46	1·109	0·114	0·186	0·060	100·3	99·4
End of work IV	101·07	100·22	1·115	0·157	0·187	0·070	101·0	100·05

* Calculated on 31 degrees of freedom.

O., Oxford; S., Singapore.

Varied environmental conditions (the factorial experiment)

The factorial experiment as already explained extends the comparison between the tropical and non-tropical subjects to sixteen different sets of conditions. The results detailed below confirm in most respects the findings in the uniformity trials.

Total sweat loss. Table 7 and Fig. 4 give for comparison the results obtained in the sixteen different sets of conditions at Oxford and the corresponding values of the Singapore group. Each of the means shown in Table 7 is the mean of two observations, corrected by covariance on the uniformity trials; that is to say the means have all been adjusted to the value to be expected for a subject whose sweat loss was equal to the mean of the thirty-two values of the appropriate uniformity trial. Separate regression coefficients have been used for each combination of dry-bulb and work rate, since these differ widely. The

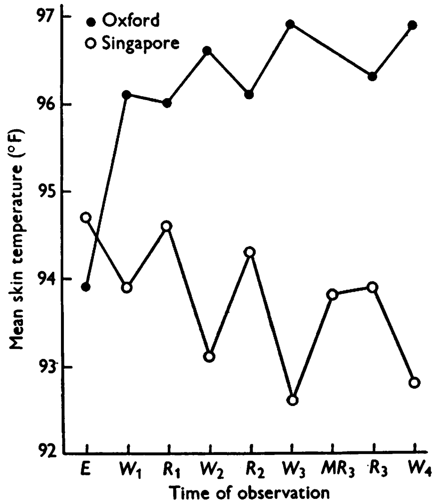

Fig. 2. Mean skin temperatures (° F) during uniformity trials at Oxford and Singapore. *E*, on entry; *W*, end of work period; *R*, end of rest period; MR_3, middle of third rest period (Singapore only).

TABLE 5. Mean skin temperature during uniformity trials (° F)

	Mean		Standard deviation		S.E. of mean	
	O.	S.	O.	S.	O.	S.
On entry	93·9	94·7	1·42	1·33	0·24	0·24
End of work I	96·1	93·9	1·05	1·40	0·18	0·25
End of rest I	96·0	94·6	1·01	1·40	0·17	0·25
End of work II	96·6	93·1	1·35	1·14	0·23	0·20
End of rest II	96·1	94·3	1·18	1·56	0·20	0·28
End of work III	96·9	92·6	1·45	0·87	0·24	0·15
End of rest III	96·3	93·9	1·16	1·30	0·20	0·23
End of work IV	96·9	92·8	1·50	1·26	0·26	0·22

O., Oxford; S., Singapore.

standard errors, which are average values, are thus each based on 7 degrees of freedom. They are applicable to comparisons within either the tropical or non-tropical group; that is to say comparisons, such as the average effect of air speed, which are not affected by a constant difference between Oxford and Singapore. The standard errors for comparisons between the two groups would be slightly larger, since these comparisons are also affected by the sampling errors of the uniformity-trial means.

The results, on the whole, bear out the finding of the uniformity trials. In all eight environments in which work was done, and in six of the eight in which the men remained at rest, the Singapore subjects sweated more than those at Oxford. Of the factors which influence the sweat rate, the dry-bulb temperature (D) and the work rate (P) have a large effect under all conditions studied

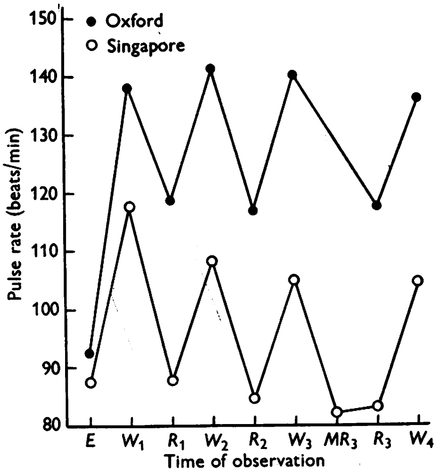

Fig. 3. Standing pulse rates (beats/min) during uniformity trials at Oxford and Singapore. E, before entry; W, end of work period; R, end of rest period; MR_3, middle of third rest period (Singapore only).

TABLE 6. Pulse rates during uniformity trials (beats/min)

	Mean		Standard deviation		S.E. of mean	
	O.	S.	O.	S.	O.	S.
Before entry	92·3	87·4	15·6	15·2	2·6	2·8
End of work I	138·0	117·6	17·8	18·2	2·8	3·2
End of rest I	118·4	87·6	13·8	16·6	2·2	3·0
End of work II	141·0	108·0	18·4	20·0	3·0	3·6
End of rest II	116·6	84·4	16·0	14·8	2·6	2·6
End of work III	140·0	104·8	16·8	18·4	2·8	3·2
End of rest III	117·2	83·0	16·8	13·8	2·8	2·4
End of work IV	136·0	104·4	18·8	16·0	3·2	2·8

O., Oxford; S., Singapore.

(Table 8). The increase in sweat loss induced by these two factors is greater at Singapore than at Oxford. Air speed (A) and wet-bulb temperature (W) have effects which vary with the dry-bulb temperature and level of activity (Table 7). The rise in air speed from 20 to 300 ft./min induces an increased sweat loss at 120° F dry-bulb, an effect which is significantly greater on the average in the tropical subjects. At 90° F the increased air velocity brings about a decided fall in sweat output of the tropical subjects; at Oxford the reduction is much smaller and not significant. The results are in line with other investigations (Dunham, Holling, Ladell, McArdle, Scott, Thomson & Weiner, 1946; Adam, Ellis, Irwin, Thomson & Weiner, 1952) which show that an increase in air speed from a low value such as 50 ft./min to a high value such as 300 ft./min will decrease sweat output when the air temperature is below skin

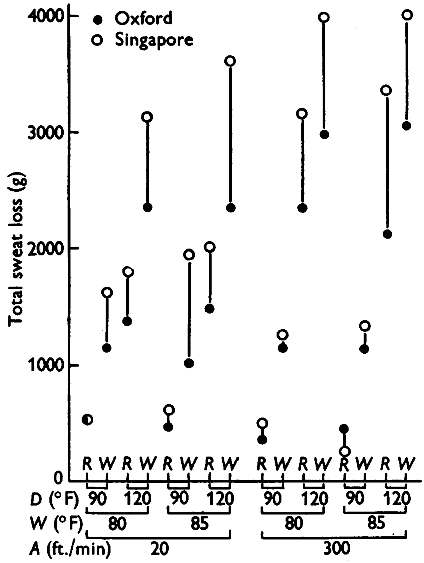

Fig. 4. Total sweat losses (g) during factorial experiment at Oxford and Singapore. *R*, resting subjects; *W*, working subjects.

Table 7. Total sweat loss in tests of varied conditions—mean values (g/4 hr)

Dry-bulb temperature (° F)	Wet-bulb temperature (° F)	Air speed (ft/min)	'Working' subjects: Oxford	'Working' subjects: Singapore	'Resting' subjects: Oxford	'Resting' subjects: Singapore
90	80	20	1151	1624	538	532
		300	1158	1268	366	505
	85	20	1024	1946	483	611
		300	1142	1340	456	264
S.E.			81		40	
120	80	20	2342	3120	1384	1806
		300	2976	3984	2348	3140
	85	20	2346	3604	1490	2010
		300	3050	4005	2117	3344
S.E.			93		69	

temperature, but may increase the sweat loss when the air is hotter than the skin. Increasing the wet-bulb temperature from 80 to 85° F causes a small but generally consistent increase in sweat loss in the tropical subjects; the Oxford subjects show only a slight and insignificant increase. Other investigations on artificially acclimatized subjects, while confirming that an increase of sweat loss generally occurs when the wet-bulb is raised from 80 to 85° F, indicate that the increase is usually quite small.

Rectal temperature. The mean rectal temperature of the men taken before entering the hot room on this second, factorial-test, day at Oxford did not differ significantly from that taken at Singapore (Singapore 99·15° F, Oxford 99·00° F, difference 0·15 ± 0·119° F). Nor had there been any difference on the occasion of the previous uniformity test (Singapore 99·64° F, Oxford 99·48° F, difference 0·16 ± 0·104° F). It will be seen from these figures, however, that on the second day the rectal temperature before entry into the hot room was lower than that measured in the test 3 days before. This was the case at both centres;

TABLE 8. Table of mean values for total sweat loss (grams)

	W_1		W_2	A_1		A_2	P_1		P_2	Mean
				Oxford						
D_1	792		769	795		766	454		1108	781
	(1439)		(1496)	(1091)		(1844)	(1372)		(1562)	
D_2	2231		2265	1886		2610	1826		2670	2248
Interaction		28			376			10		
Mean	1512		1517	1341		1688	1140		1889	
				Singapore						
D_1	970		1045	1169		846	478		1538	1008
	(2038)		(2163)	(1455)		(2745)	(2072)		(2127)	
D_2	3008		3208	2624		3591	2550		3665	3108
Interaction		62			645			28		
Mean	1989		2126	1896		2219	1514		2601	

For main effects, the S.E. of a single mean is 21·82. For first-order interactions, the S.E. of a single mean is 30·86. The figures in brackets show the changes on going from D_1 to D_2.

at Singapore the mean decrease was 0·491° F (± 0·0456) and Oxford 0·472 (± 0·0902). The decrease was remarkably constant, and is probably explained by the diurnal variation in body temperature. The uniformity trials began at 1.0 p.m. and the factorial experiments at 9.0 a.m. The expected difference between the rectal temperature at 9.0 a.m. and 1.0 p.m. is 0·60° F at Oxford and 0·56° F at Singapore (Adam, Collins, Ellis, Irwin, Jack, John, Jones, Macpherson & Weiner, 1955), which is in reasonable agreement with the observed differences.

During the 4 hr exposure in the hot room, and in contrast to the finding of the previous uniformity trials, no difference in rectal temperature between the Oxford and Singapore subjects was observed. At the end of the first and second work periods the Oxford rectal temperatures were slightly higher than those at Singapore, but this effect did not persist; thereafter the Singapore temperatures were slightly higher. The rectal temperatures were affected by changes in level of dry-bulb temperature, wet-bulb temperature and the work rate to a similar extent at both test centres. The main effects are shown in Table 9.

Skin temperature. In confirmation of the finding in the uniformity trials the skin temperatures at Oxford measured under the varied conditions of the factorial experiment were consistently higher than those at Singapore, as shown in Table 10. On the average the effect of increasing the air temperature and the air speed is similar in the two places, but an increase in the wet-bulb temperature is without effect in Singapore although it results in a slight rise at Oxford, and an increase in the rate of work is without effect at Oxford although it produces a slight fall at Singapore.

TABLE 9. Rectal temperatures in relation to dry-bulb temperature (*D*), wet-bulb temperature (*W*) and level of activity (*P*). All values in ° F

			Average effects			
	Mean values Oxford and Singapore	S.E.	*D* (120° F – 90° F)	*W* (85° F – 80° F)	*P* (work – rest)	S.E.
Before entry	99·08	0·062	0·19	0·01	0·04	0·125
End of work I	99·88	0·062	0·57	0·07	1·18	0·125
End of rest I	99·75	0·075	1·01	0·25	0·66	0·150
End of work II	99·98	0·056	0·90	0·25	1·24	0·112
End of rest II	99·68	0·056	1·12	0·35	0·75	0·112
End of work III	99·95	0·050	1·17	0·39	1·51	0·100
End of rest III	99·40	0·059	1·42	0·45	0·46	0·119
End of work IV	99·80	0·062	1·38	0·38	1·23	0·125

TABLE 10. Mean skin temperatures (° F) in relation to dry-bulb (*D*), wet-bulb (*W*), air speed (*A*) and level of activity (*P*)

		Oxford	Singapore
D	90° F	94·52	92·73
	120° F	97·44	95·09
W	80° F	95·40	93·02
	85° F	96·56	92·82
A	20 ft./min	96·18	93·62
	300 ft./min	95·77	92·73
P	Rest	95·99	93·29
	Work	96·54	91·98

S.E. of a single mean is 0·25.

Pulse rate at end of the third work period. As in the uniformity test, there is a significantly higher pulse rate in Oxford (Table 11). Increasing the dry-bulb temperature from 90 to 120° F produces a significant effect in both localities. Increasing the rate of energy expenditure produces a similar significant increase, an average increment of about 30 beats/min. It should be noted, however, that for subjects working at dry-bulb 120° F pulse rates are practically as high in Singapore as in Oxford. The wet-bulb effect is slightly greater in Singapore—at Oxford it is not significant. There is a suggestion both at Oxford and Singapore that the effect of air speed depends on the dry-bulb temperature. Increasing the air speed from 20 to 300 ft./min produces at dry-bulb 90° F a fall in the pulse rate but at dry-bulb 120° F a rise in pulse rate. This is true both at Oxford and Singapore.

TABLE 11. Table of mean values for pulse rate at end of work III (beats/min.)

	W_1	W_2	A_1	A_2	P_1	P_2	Mean
				Oxford			
D_1	96	102	102	96	86	112	99
	(33)	(32)	(24)	(40)	(33)	(32)	
D_2	129	134	126	136	119	144	131
Interaction	0		8		0		
Mean	112	118	114	116	102	128	
				Singapore			
D_1	70	84	80	74	69	85	77
	(39)	(46)	(35)	(50)	(28)	(57)	
D_2	109	130	115	124	97	142	120
Interaction	4		8		14		
Mean	90	107	97	99	83	114	

For main effects, the S.E. of a single mean is 3·0. For first-order interactions, the S.E. of a single mean is 4·3. The figures in brackets show the changes on going from D_1 to D_2.

DISCUSSION

Acclimatization

The foregoing results taken together indicate that the tropical group in the course of their 18 months residence in Singapore had acquired a tolerance of hot environments considerably superior to that possessed by their counterparts in England and, by inference, superior to that which they themselves possessed before their arrival in the tropics. This is what common experience would lead one to expect. It is a familiar observation that, although the newcomer to the tropics is more distressed by the environment than the established resident, in a relatively short space of time he adapts to his environment and his distress diminishes—a phenomenon usually described as acclimatization.

Acclimatization may be formally defined as an adaptative process which results in a reduction in the physiological strain produced by the application of a constant environmental stress. Environmental stress is conveniently described in terms of the air and radiant temperature, humidity, air speed, rate of energy expenditure and amount of clothing worn. If the environmental stress is to remain constant, not only must the physical factors of temperature, humidity and air speed remain constant, but also the associated variables—rate of working and the amount of clothing. Undoubtedly the resident of the tropics wears less clothes than the inhabitant of temperate climates and the newcomer may, indeed, progressively shed more of his clothing. It is also possible that he may reduce his rate of energy expenditure, by doing less work or producing the same work output more economically by the elimination of adventitious movements and more complete relaxation during rest. Similarly, he may change his dietary pattern and consume more water and salt. The question therefore arises whether natural acclimatization may not be entirely behavioural and unaccompanied by any physiological change.

In the experiments at Oxford and Singapore the two groups of subjects, the tropical and non-tropical, were subjected to the same environmental stress. Not only were the physical conditions of temperature, humidity and air speed strictly controlled, but so also was the rate of working and the amount of clothing worn. The reduction in the physiological strain produced in the tropical as compared with the non-tropical cannot have been the result of behavioural differences. It may therefore be concluded that, even if there is a large behavioural element in the process of natural acclimatization, there is also an important degree of physiological adaptation.

Criteria of acclimatization

In the terms of the definition given, assessment of the degree of acclimatization requires some method of measuring the physiological strain produced by the environment. The first and most obvious measure is provided by the degree of discomfort or distress experienced by the subject when exposed to a standard hot environment, but distress cannot be expressed quantitatively with precision, and comparisons are difficult and at best unreliable. Much the same difficulties are met with when an attempt is made to measure ability to work or even survival time.

At first sight it would appear that the best objective measure of physiological strain is provided by deep-body temperature. If man is a homothermous animal, it is to be presumed that adaptation will be directed towards the maintenance of his internal thermal environment at some value, divergence from which will be opposed. The rectal temperatures observed during the uniformity trials indicate that in the tropical group the deep-body temperature was displaced less from its initial value than in the non-tropical group. To this extent the adaptative mechanism has been successful and the physiological strain diminished. But adaptation cannot be considered to be successful if one component of the internal environment is kept constant at the expense of an unacceptable variation in some other component; for example, if a reduction in the increment in deep-body temperature was achieved by cardiovascular adjustments that in themselves could be considered as undesirable. This desideratum appears also to be satisfied because the pulse rate here is lower in the tropical than in the non-tropical group. The skin temperature is also lower, which probably adds to the comfort or relative freedom from distress of the subjects.

In practice, however, it is probably unwise to rely entirely on any one single measure, not even deep-body temperature, to provide an estimate of physiological strain. This is well exemplified by the results of the factorial experiment.

They are in agreement with the results of the uniformity trials in that the men in Singapore had lower pulse rates, lower skin temperatures and greater sweat losses than the men in Oxford, but no difference could be demonstrated in the rectal temperatures of the two groups.

It is hard to say just why this should be, especially in view of the decisive difference in the rectal temperatures found in the uniformity trials. It could be, of course, that the design of the factorial experiment was unsuitable for demonstrating the small differences to be expected, especially at the lower levels of stress. Nor can the possibility of acclimatization occurring within the experiment be entirely excluded. In his investigations of the process of acclimatization to heat in Bantu miners, Dreosti (1935) showed that even a single previous exposure to hot conditions was sufficient to effect an appreciable decrease in the rise in body temperature produced by a standard hot environment, and that this decrease, as would be expected, was most marked among the least acclimatized. Similarly, one would expect such a change to occur in the less acclimatized Oxford group rather than in the more acclimatized Singapore group.

The use of the divergence of the rectal temperature from its set value as a measure of physiological strain has much to recommend it on theoretical grounds. The decreased divergence on acclimatization would indicate that the sensitivity of the regulating mechanism has increased, that is, a smaller divergence produces a greater correction. The difficulty arises in determining the basal value from which it is caused to diverge. Man is not strictly speaking a homothermous animal, probably a better word is homoiothermous. His body temperature is not fixed at one value, but may adjust its level according to circumstances and then regulate about this new level. Examples of this are to be seen in the diurnal variation already noted on p. 568, the effect of fever (Ferres *et al.* 1954), of work rate (Nielsen, 1938), geographic location (Adam & Ferres, 1954), and the well-known variations between individuals.

The increased sweat rate observed in the tropical group raises a number of interesting points. In general, an increase in the amount of sweat secreted is considered to indicate an increase in the physiological strain produced by the environment. This concept has been used successfully by McArdle & Dunham, Holling, Ladell, Scott, Thomson, Weiner (1947) as the basis of a scale of environmental stress. There is therefore an obvious paradox. In one set of circumstances an increase in sweat rate is taken to indicate an increase in physiological strain, and in another set of circumstances is taken to indicate greater acclimatization.

In the uniformity trials the skin temperature of the subjects is below air temperature so that heat is dissipated only by evaporation of water from the skin and lungs. Heat is gained by the body from two sources, an internal, the metabolic heat production, and an external, convective and radiant heat gain from the environment. The equation representing the heat balance of the subjects may be written as

$$E = M + (R + C) - S,$$

where M = metabolic heat production, $R + C$ = heat *gain* by radiation and convection, E = heat loss by evaporation, S = heat 'stored' in the body.

As a consequence of lower skin temperatures (Table 5), heat gain by radiation and convection in the tropical group would be greater than in the Oxford subjects and, since both skin and rectal temperatures (Table 4) rise less, the heat of storage in the tropical group is lower. It follows, for both these reasons, that E must be greater than that of the non-tropical subjects, if heat of metabolism remains unchanged. That an increased evaporative loss could well be attained is of course suggested by the increased sweating which is found to accompany tropical residence in the present investigation. The increase in heat loss by evaporation would, however, be reduced to a greater or lesser degree if body heat production was in fact lower in the tropical group. There is some evidence that the basal metabolism of Europeans is reduced by residence in hot climates, though not all Europeans necessarily undergo this reduction (Macgregor & Loh, 1941), but there is no convincing evidence that the energy expenditure on a standardized task such as step-climbing varies with the environmental temperature or the degree of acclimatization.

To decide what increase in evaporative loss is required to balance the greater heat gain of the tropical subjects requires an estimate of this gain. The calculation is necessarily a rough one. The estimation of storage is only approximate, and we cannot be certain of the values for the physical constants of heat transfer by radiation and convection, as we must rely on average values for men studied in the rather different conditions of the experiments of Nelson, Eichna, Horvath, Shelley & Hatch (1947).

Calculation of $S + (C + R)$ in the uniformity trials shows that the excess heat load 'handled' by the Singapore subjects averages 170 kcal in 4 hr. It can be seen that the calculated greater heat load could easily be met by the observed increase in average sweat loss. The increased evaporation required to meet the excess heat load at Singapore amounts to about 300 g of sweat and the observed excess at Singapore is 480 g. Not all this sweat was available for evaporation; at Oxford the average loss of sweat as drippage was nearly 100 g, i.e. about 6% of the sweat output. Even allowing 10% for waste in this way, the higher sweat loss at Singapore would appear to meet adequately the greater heat gain of the 'tropicalized' subjects.

Similar calculations may be applied to the factorial experiment, although the difference between the two groups is not so clear-cut. In those cases in which the skin temperature is above air temperature the heat loss by convection and radiation is less in the tropical than the non-tropical, which amounts to the same thing as an increase in heat gain. The results obtained are in conformity with those described for the uniformity trials. The two air speeds, 20 and 300 ft./min, have to be considered separately. The excess heat load borne by the Singapore subjects is found to be at 20 ft./min 120 kcal, and at 300 ft./min 214 kcal, in 4 hr exposure, requiring an increase in evaporation of 207 and 369 g of water respectively. The excess of water lost by sweating at Singapore was actually found to average 512 and 629 g for the two groups of tests.

These calculations are presented for illustrative purposes only but they suggest that, although some of the increased sweat loss in the tropical group is a necessary accompaniment of the increased radiant and convective heat gain, some of the increase may well be wasteful. Perhaps an excessive production of unevaporated sweat is characteristic of the short-term acclimatization process, as seen in Europeans, for there is some evidence that indigenous tropical people differ from 'tropicalized' Europeans in their more económical sweating (Adam, Ellis & Lee, 1953; Lee & Weiner, unpublished; Wyndham, Bouwer, Devine & Paterson, 1952). The lesser sweating of native-born subjects is evident even when the sweat rate is augmented by further 'acclimatization' in a hot chamber at unusually severe conditions. This has been observed in local Chinese, Malays and Indians at Singapore, and a similar claim is made for Bantu in South Africa when tested in conditions producing high sweat rates.

Artificial acclimatization

Comparison of the reactions of the tropical with those of the non-tropical group shows that, when exposed to the same hot environment, the former produced more sweat and suffered a smaller increment of body temperatures and heart rate than the latter. Therefore, the effect of one season of residence in tropical climates on young and active European men is to induce in them changes in their responses to heat similar to those found in men repeatedly exposed to hot environments in experimental hot rooms. It is to be concluded that the changes observed in laboratory experiments are identical with those that occur naturally. In the laboratory, as in the natural state, these changes are accompanied by an increased ability to perform muscular work and a decrease in the discomfort experienced. It would appear, then, that the laboratory phenomenon is correctly described as 'artificial acclimatization'.

Conclusions

It is concluded that:

(*a*) Residence in the tropics for an average period of 18 months results in an increased ability to withstand the stress of hot environments.

(*b*) Since in these two investigations all the factors which contribute to environmental stress, including the rate of energy expenditure and amount of clothing worn, were accurately controlled, this process of 'natural acclimatization' must involve physiological as well as behavioural adaptation.

(c) The phenomenon of natural acclimatization to tropical climates if not identical with, at least has the same physiological basis as the 'artificial acclimatization' produced experimentally in the laboratory.

SUMMARY

1. In order to determine whether the 'natural acclimatization' produced by residence in a hot climate is identical with the 'artificial acclimatization' produced in the laboratory, two identical series of experiments were performed, one in England and the other at Singapore.

2. The thirty-two subjects in both series of experiments were similar in every respect except that the tropical group had spent on the average 18 months in the tropics.

3. Each man was exposed to hot conditions twice with an interval of 4 days between exposures.

4. On the first occasion (uniformity trial) all men experienced the same environmental conditions, and worked at the same rate. On the second occasion the subjects were divided into sixteen pairs by lot, and each pair was exposed to one of the sixteen combinations provided by a factorial experiment with two levels each of air temperature, humidity, air speed and energy expenditure.

5. The results of the factorial experiment were corrected by means of analysis of covariance using the results of the uniformity trial, and thus the effects of a wide range of conditions were determined without repeated exposure of the subjects with consequent acclimatization.

6. The two uniformity trials showed that the tropical group secreted more sweat, their rectal temperatures rose less, their pulse rates were lower, and their mean skin temperatures were also lower. The skin temperature behaved differently in the two groups. In the tropical group it fell with work and rose on resting; in the non-tropical group it rose on working and fell with rest.

7. The results of the factorial experiments confirmed these findings, except that there was no significant difference between the rectal temperatures in the two groups. The effect of varying the level of the various factors was similar in the two groups.

8. These results and their relationship to the phenomenon of acclimatization are discussed. It is pointed out that the differences observed between the tropical and the non-tropical group are those that occur during the 'artificial acclimatization' which results from repeated exposure to hot environments in the laboratory.

9. It is concluded that the superior ability to withstand hot environments exhibited by those who live in the tropics involves physiological as well as

behavioural adaptation, and that the physiological basis of this 'natural acclimatization' is identical with that of the 'artificial acclimatization' produced in the laboratory.

REFERENCES

ADAM, J. M., COLLINS, J. A. G., ELLIS, F. P., IRWIN, J. O., JACK, J. W., JOHN, R. T., JONES, R. M., MACPHERSON, R. K. & WEINER, J. S. (1955). Physiological responses to hot environments of young European men in the tropics (II and III). *Spec. Rep. Ser. med. Res. Coun., Lond.*, no. R.N.P. 55/831.

ADAM, J. M., ELLIS, F. P., IRWIN, J. O., THOMSON, M. L. & WEINER, J. S. (1952). Physiological responses to hot environments of young European men in the tropics (I). *Spec. Rep. Ser. med. Res. Coun., Lond.*, no. R.N.P. 52/721.

ADAM, J. M., ELLIS, F. P. & LEE, T. S. (1953). Daily variations in physiological values for European and Asian men working at high temperatures in the tropics. *Spec. Rep. Ser. med. Res. Coun., Lond.*, no. R.N.P. 53/749.

ADAM, J. M. & FERRES, H. M. (1954). Observations on oral and rectal temperatures in the humid tropics and in a temperature climate. *J. Physiol.* **125**, 21*P*.

ADAM, J. M., JACK, J. W., JOHN, R. T., MACPHERSON, R. K., NEWLING, P. S. B. & YOU, P. S. (1953). Physiological responses to hot environments of young European men in the tropics (IV). *Spec. Rep. Ser. med. Res. Coun., Lond.*, no. R.N.P. 53/767.

BEAN, W. B. & EICHNA, L. W. (1943). Performance in relation to environmental temperature. *Fed. Proc.* **2**, 144–158.

DREOSTI, A. O. (1935). The results of some investigations into the medical aspect of deep mining in the Witwatersrand. *J. chem. Soc. S. Afr.* **36**, 102–129.

DUNHAM, W., HOLLING, H. E., LADELL, W. S. S., MCARDLE, B., SCOTT, J. W., THOMSON, M. L. & WEINER, J. S. (1946). The effects of air movement in severe heat. *Spec. Rep. Ser. med. Res. Coun., Lond.*, no. R.N.P. 46/316.

FERRES, H. M., FOX, R. H., JACK, J. W., JOHN, R. T., LIND, A. R., MACPHERSON, R. K. & NEWLING, P. S. B. (1954). Physiological responses to hot environments of young European men in the tropics (V). *Spec. Rep. Ser. med. Res. Coun., Lond.*, no. R.N.P. 54/812.

LADELL, W. S. S. (1947). Effects on man of high temperatures. *Brit. med. Bull.* **5**, 5–8.

MCARDLE, B. & DUNHAM, W., HOLLING, H. E., LADELL, W. S. S., SCOTT, J. W., THOMSON, M. L., WEINER, J. S. (1947). The prediction of the physiological effects of warm and hot environments. *Spec. Rep. Ser. med. Res. Coun., Lond.*, no. R.N.P. 47/391.

MACGREGOR, R. G. S. & LOH, G. L. (1941). The influence of a tropical environment upon the basal metabolism, pulse rate, and blood pressure in Europeans. *J. Physiol.* **99**, 496–509.

NELSON, N. A., EICHNA, L. W., HORVATH, S. M., SHELLEY, W. B. & HATCH, T. F. (1947). Thermal exchanges of man at high temperatures. *Amer. J. Physiol.* **151**, 626–652.

NIELSEN, M. (1938). Die Regulation der Körpertemperatur bei Muskelarbeit. *Skand. Arch. Physiol.* **79**, 193–230.

ROBINSON, S., TURRELL, E. S., BELDING, H. S. & HORVATH, S. M. (1943). Rapid acclimatization to work in hot climates. *Amer. J. Physiol.* **140**, 168–176.

WYNDHAM, C. H., BOUWER, W. V. D. M., DEVINE, M. G. & PATERSON, H. E. (1952). Physiological responses of African labourers at various saturated air temperatures, wind velocities and rates of energy expenditure. *J. appl. Physiol.* **5**, 290–298.