THE EFFECTS OF AIR TEMPERATURE AND VELOCITY AND OF VARIOUS FLOORING MATERIALS ON THE THERMAL SENSATIONS AND SKIN TEMPERATURE OF THE FEET

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(With 6 Figures in the Text)

I. INTRODUCTION

When complaints of cold feet are made in rooms with concrete floors, there is a tendency amongst people to attribute the discomfort directly to the concrete. It is, of course, obvious that to a bare foot concrete feels very much colder than a cork or wood surface; but it is not so apparent how a floor of comparatively high thermal conductivity such as concrete can appreciably affect the feelings of warmth when the feet are shod. Even the light footwear usually worn by women, being composed of more than one layer of material, must offer considerable resistance to heat loss. In addition, the area of the sole of the shoe in actual contact with the floor is small.

The sole of the foot may possibly be a region which is thermally very sensitive. On the other hand, the discomfort of the feet may be due simply to general chilling due to low air temperatures, for stone and concrete floors are often used in situations which tend to be cold. In this connexion Nielsen (1947) found that a decrease in the environmental temperature caused a decrease in the temperature of the extremities, while other parts of the body were only slightly affected. He noted that sensations of 'uncomfortable cold' were mainly due to cooling of the lower extremities. As Krogh (1943) points out, 'The feet react in a particular way to cold conditions. Practically no heat production takes place in them and they are warmed only by the circulation of the blood through them. When an individual begins to feel cold, the blood supply to the feet is usually more or less cut off and the temperature of the feet usually falls strongly.' If this is so, the remedy is not to put more lagging on the sole of the foot but to improve the heating of the room. A 'cold' floor, i.e. one of comparatively high thermal conductivity, is only one of the factors which have to be considered when there are complaints of cold feet, and it must be given its true evaluation in relation to other factors such as air temperature and draughts which may be of equal or even of greater importance. The experiments described below have been conducted with these considerations in mind.

II. EXPERIMENTS

The tests were made in the Heating Laboratory of the Building Research Station, Watford. This is a room of 2000 cu.ft. volume and 216 sq.ft. floor area, where the temperatures of the air and of the walls can be controlled with considerable accuracy. The ventilation rate was maintained at about two air changes per hour, and the air movement in the room never exceeded 20 ft. per min. It was not possible to control the humidity of the air inside the room, but the relative humidity was usually about 50%. Experiments were made at 65 and 55° F., with the walls and air controlled at the same temperature. Different parts of the wooden floor of the room were covered with slabs of the flooring material to be tested. Each slab was approximately 4 sq.ft. in area and from 1½ to 2 in. thick. The materials were:

	k
(1) Concrete	6·8
(2) Cork tile	0·7
(3) Cork slab	0·4
(4) Linoleum	1·6
(5) Rubber sheet	1·9
(6) Wood	1·0

The thermal conductivities (k) are approximate values, and are expressed in B.TH.U. per sq. ft. per hr., per degree F., per in. thickness of material. Care was taken to ensure that before any tests were carried out the slabs were at the same temperature as the room.

The two male subjects of the tests were the investigators themselves. They were both aged about 35 years, and were of normal physique and in good health. Some tests were made when their feet were bare, and others when they were shod. In the latter instance, the subjects wore normal-weight shoes, with soles of medium thickness, and medium-weight to light-weight woollen socks. Most of the experiments with bare feet were done between the months of April and May, and the shod feet tests were carried out between June and July. In other tests, which were carried out during August 1947, the effects of floor draughts on shod feet were investigated. The foot temperatures were measured on the following

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three sites on the foot: (1) the ankle (1 in. below the medial malleolus); (2) the sole (plantar surface of the base of the hallux); and (3) the toe region (dorsum of the proximal end of the hallux). The measurements were made by means of thermocouples of 32-gauge copper and constantan. The leads were securely held by an adjustable leather strap made to fasten below the knee, and the junctions were attached to the skin by small pieces of adhesive tape. For the numerical assessment of thermal sensations, the scale devised by Bedford (1936), viz.

Much too warm	+3	Comfortably cool	−1
Too warm	+2	Too cool	−2
Comfortably warm	+1	Much too cool	−3
Comfortable	0		

was used to record: (*a*) sensations of bodily warmth excluding, as far as possible, sensations on the feet; and (*b*) local sensations of comfort referred to the feet at the places where skin surface temperatures were measured.

Procedure

As a routine, the mean radiant temperature, the air temperature, the relative humidity, the air velocity, and the surface temperature of the floor material under test, were measured at the beginning and end of each experiment. No serious drift in the temperature of the room from the required levels of 55 and 65° F. resulted from the presence of the subjects during the experiment. Before entering the controlled room for either a shod or a bare foot test, the subjects attached the thermocouples to their feet in an outer room where the temperature never fell below 60° F., and they remained there for sufficient time to allow the feet to become comfortable (zero on the warmth scale).

The subjects then entered the test room and recorded the various environmental readings referred to above. Some preliminary measurements of foot temperatures were then made. The feelings of warmth, however, and not the level of skin temperature, decided when the test began. When subjects wore shoes, they sat at a table with their feet on the flooring material to be tested, and recorded their skin temperatures and sensations of warmth for a period of not less than 60 min., and usually of 90 min. When the bare feet were tested, the procedure was similar except that, after removing their socks and shoes the subjects placed their bare feet on the floor material, and recorded their skin temperatures as soon as possible after contact, and thereafter at intervals of 3 min. for at least 30 min., and usually 60 min.

For the draught tests, the subject sat with a shod foot at the mouth of a duct about 5 ft. long and 1 sq.ft. in cross-section. At the other end of the duct was set an axial fan the speed of which was controlled by a Variac transformer. The foot was placed on a metal tripod, 6 in. high, with the top bound with insulating material. Almost the whole foot was thus exposed to the effects of the moving air.

III. RESULTS

(1) *Shod feet*

(*a*) *Changes in sensation with the feet on different floor materials*

Tables 1 and 2 show the mean initial and final sensations, and the mean changes in sensation experienced while sitting for 60 min. at 55 and 65° F. with the shod feet on different floor materials. They refer to the sensations of warmth on different parts of the feet, and to the general sensations of warmth. For subject 1, in whom an initial rise in skin temperature was usually observed at 55° F., the differences in temperature and sensation over 60 min. have been calculated for the period from 15 to 75 min. after the start of an experiment, i.e. from the time when an appropriate plateau level of skin temperature was reached. Figs. 1 and 2 show that at an air temperature of 55° F. after the initial rise, the fall in skin temperature was approximately linear.

Inspection of the actual changes in sensation on the sole on different floors (Table 1), shows that the difference between the change in sensation on concrete and on cork is 0·5 units, the smaller change in sensation occurring with cork. Although the thermal conductivity of wood is intermediate between those of cork and concrete, the change in sensation with wood flooring was no less than with concrete. There was but little difference between the effects of the remaining materials and those of concrete. The differences are not statistically significant, as may be seen from Table 5 where the data for cork and concrete floors are compared.

The trunk tends to be less affected by changes of environmental temperature than the extremities. This is illustrated by averaging separately the changes in sensation for the sole, toe, ankle and the whole body irrespective of floor surface as shown in Table 1. Ankle and toe changes are equal and the overall body change is 0·7 units of sensation less than the former. The mean change on the sole over a 60 min. period is only 0·2 units greater than that on the ankle, a difference which is statistically insignificant.

Among other factors causing changes in sensation on the feet sufficient to outweigh the effects of different floor materials, the most important is probably the environmental air temperature. The mean change in body sensations of both subjects during 60 min. at 55° F. is 0·5 units and the fall in ankle sensation is about twice this amount (Table 1). This is important as one does not always dissociate one's general body sensation from that of the feet when

Table 1. *The warmth votes of the two subjects have been averaged and the initial and final mean values are given together with the changes occurring after sitting for* 60 *min. with the shod feet on different flooring materials in the room at* 55° F. *air temperature*

	Sensations of warmth on			
	Sole	Toe	Ankle	Body excluding feet
Concrete A:				
Initial	0·5	0·5	0·3	−0·1
Final	−1·1	−1·0	−0·8	−0·6
Change	−1·6 (−0·5)*	−1·5	−1·1	−0·5
Concrete B:				
Initial	−0·3	0·0	0·0	−0·5
Final	−1·8	−1·5	−1·0	−1·0
Change	−1·5 (−0·5)	−1·5	−1·0	−0·5
Rubber on concrete:				
Initial	0·3	0·3	0·3	−0·4
Final	−0·9	−1·7	−1·2	−0·5
Change	−1·2 (0·3)	−2·0	−1·5	−0·1
Linoleum on concrete:				
Initial	−0·2	0·0	0·0	−1·3
Final	−1·3	−1·3	−1·3	−1·5
Change	−1·1 (0·2)	−1·3	−1·3	−0·2
Cork on concrete:				
Initial	−0·3	−0·2	0·0	−0·7
Final	−1·3	−1·3	−1·3	−1·4
Change	−1·0 (0·3)	−1·1	−1·3	−0·7
Wood:				
Initial	0·3	−0·4	−0·5	−0·7
Final	−1·4	−1·8	−1·5	−1·4
Change	−1·7 (−0·7)	−1·4	−1·0	−0·7
Cork:				
Initial	0·3	—	−0·4	−0·6
Final	−0·8	—	−1·5	−1·5
Change	−1·1 (0·0)	—	−1·1	−0·9
Mean:				
Initial	0·1	0·0	0·0	−0·6
Final	−1·3	−1·2	−1·2	−1·1
Change	−1·4 (−0·2)	−1·2	−1·2	−0·5

* The figures in brackets refer to the relative changes on the sole with respect to the ankle.

Table 2. *The warmth votes of the two subjects have been combined and the initial and final mean values are given together with the changes occurring after sitting for* 60 *min. with the shod feet on different flooring materials in the room at* 65° F. *air temperature*

	Sensations of warmth on			
	Sole	Toe	Ankle	Body excluding feet
Concrete:				
Initial	1·4	1·3	1·3	0·3
Final	0·4	0·4	0·4	0·0
Change	−1·0 (−0·1)*	−0·9	−0·9	−0·3
Wood:				
Initial	1·0	1·0	1·0	1·0
Final	1·0	1·0	1·0	1·0
Change	0·0 (0·0)	0·0	0·0	0·0
Cork:				
Initial	0·8	0·8	0·8	0·2
Final	1·0	1·0	1·0	0·1
Change	0·2 (0·0)	0·2	0·2	−0·1
Mean:				
Initial	1·1	1·0	1·0	0·5
Final	0·8	0·8	0·8	0·6
Change	−0·3 (−0·1)	−0·2	−0·2	0·1

* The figures in brackets refer to the relative changes on the sole with respect to the ankle.

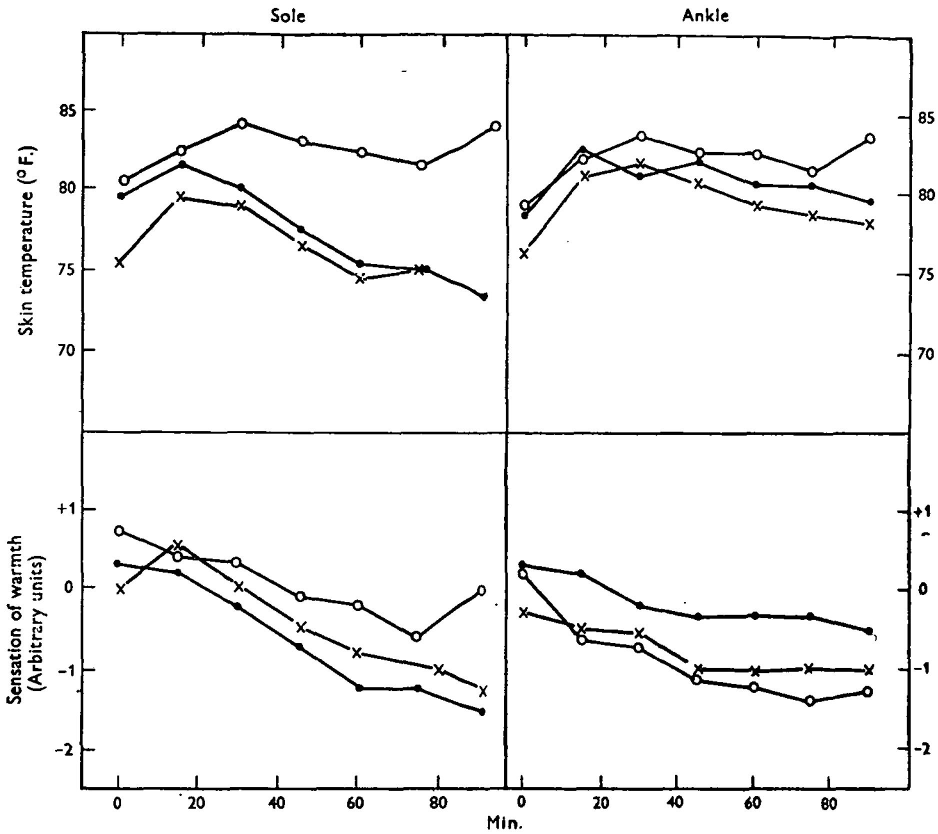

Fig. 1. Sensations of warmth and skin temperatures (° F.) of the sole and ankle of the shod foot (subject 1) plotted against time (minutes) during which the sole was in contact with concrete (●——●), wood (×——×) and cork (○——○) at 55° F.

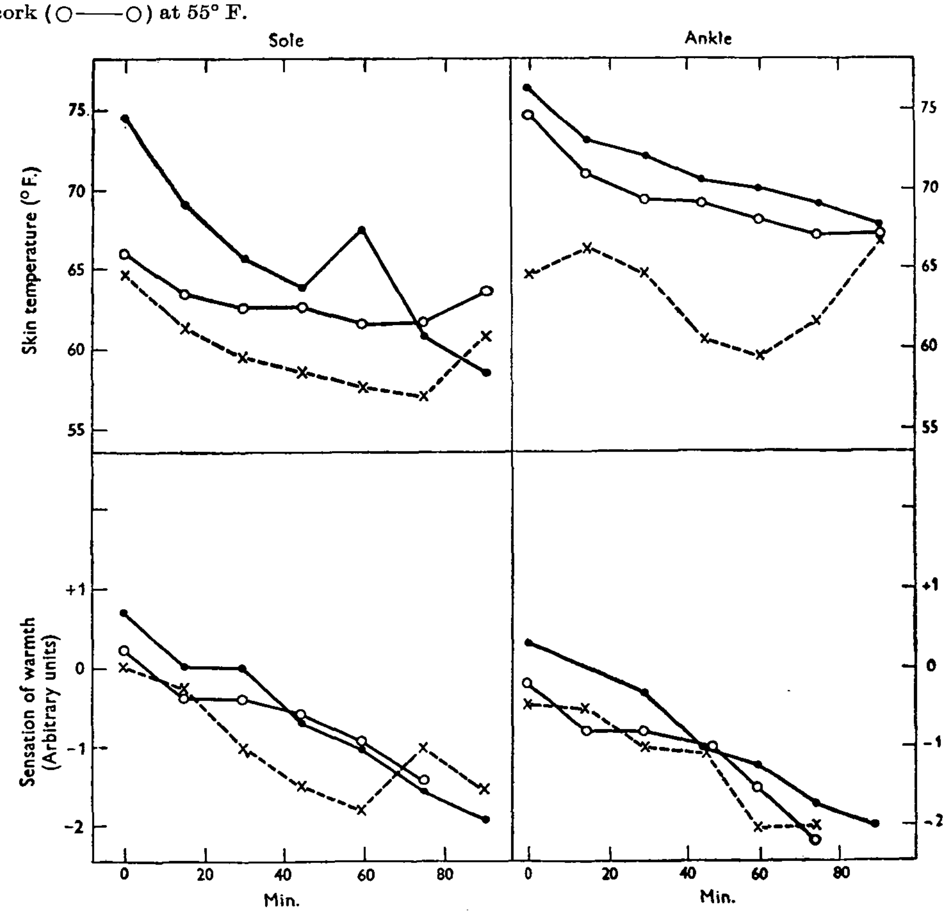

Fig. 2. Sensations of warmth and skin temperature (° F.) of the sole and ankle of the shod foot (subject 2), plotted against time (minutes) during which the sole was in contact with concrete (●——●), wood (×- - - -×) and cork (○——○) at 55° F.

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Table 3. *The skin temperatures of the two subjects have been combined and the initial and final mean values are given together with the changes occurring after sitting for* 60 *min. with the shod feet on different flooring materials in a room at* 55° F. *air temperature*

	Skin temperatures (° F.) of		
	Sole	Toe	Ankle
Concrete A:			
Initial	78·2	81·9	79·3
Final	68·6	73·9	75·0
Change	9·6 (−5·3)*	8·0	4·3
Concrete B:			
Initial	75·4	80·1	79·1
Final	67·3	70·9	74·5
Change	8·1 (−3·5)	9·2	4·6
Rubber on concrete:			
Initial	77·6	77·6	73·9
Final	68·1	68·4	69·7
Change	9·5 (−5·3)	9·2	4·2
Linoleum on concrete:			
Initial	72·4	74·7	76·6
Final	65·6	71·7	71·7
Change	6·8 (−1·9)	3·0	4·9
Cork on concrete:			
Initial	76·4	75·3	76·4
Final	71·5	71·3	70·9
Change	4·9 (+0·6)	4·0	5·5
Wood:			
Initial	72·8	76·1	72·7
Final	66·2	68·9	68·3
Change	6·6 (−2·2)	7·2	4·4
Cork:			
Initial	74·1	78·8	78·2
Final	71·6	73·6	74·7
Change	2·5 (+1·0)	5·2	3·5
Mean:			
Initial	75·3	77·8	76·6
Final	68·4	71·2	72·1
Change	6·9 (−2·4)	6·5	4·5

* The figures in brackets refer to the changes in sole temperature relative to the ankle temperature.

Table 4. *The skin temperatures of the two subjects have been combined and the initial and final mean values are given, together with the changes occurring after sitting for* 60 *min. with the shod feet on different flooring materials in the room at* 65° F. *air temperature*

	Skin temperatures (° F.) of		
	Sole	Toe	Ankle
Concrete:			
Initial	83·5	85·8	84·9
Final	83·4	85·5	83·9
Change	0·1 (+0·9)*	0·3	1·0
Wood:			
Initial	78·2	82·3	83·7
Final	77·5	80·5	82·5
Change	0·7 (+0·5)	1·8	1·2
Cork:			
Initial	81·5	83·7	83·2
Final	85·5	85·1	82·7
Change	−4·0 (−4·5)	−1·4	0·5
Mean:			
Initial	81·1	83·9	83·9
Final	82·1	83·7	83·0
Change	−1·0 (−1·9)	0·2	0·9

* The figures in brackets refer to the changes in solė temperature relative to the ankle temperature.

thinking of sensations of comfort (as the two subjects deliberately did in these tests). Instead one commonly relates one's overall sensations of comfort to the regions which are least comfortable. Thus a change of a little over one unit of sensation on the foot is sufficient to transfer an individual from the condition of general comfort to just below a comfortably cool condition, irrespective of the floor material. The results of tests at 65° F. show that the average change in sensation on the ankle (Table 2) is only $-0\cdot2$ units in 60 min. It would seem that the low air temperature in the first case is responsible for the greater part of the fall.

(*b*) *Changes in temperature of the feet on different floor materials*

Inspection of the averaged data for the two subjects in Tables 3 and 4 reveals that the actual changes in temperature on the sole correspond fairly well with the thermal conductivities of the different flooring materials, the main exception being rubber on concrete. As between cork and concrete there is a difference of 7·1° F. in temperature reduction on the sole, the concrete showing the greatest and the cork the least reduction in temperature in the series in Table 3, at 55° F. This difference is statistically significant (Table 5). The other materials, rubber on concrete excepted, are associated with temperature reductions of intermediate value, wood and linoleum on concrete producing changes of similar magnitude. The relative changes in the temperature of the sole (i.e. change in ankle temperature minus change in sole temperature) are given in brackets in Table 3. These relative changes were calculated to take into account the actual variations in the ankle temperature occurring on different days, irrespective of flooring material. Table 3 shows that the relative changes in sole temperature also correspond to the thermal conductivities of the materials. However, the temperature change on the ankle is almost constant, irrespective of the floor material, and amounts on the average to 4·5° F. after 60 min. at an air temperature of 55° F. The temperature of the sole of the foot would appear to be influenced to some extent by the different conductivities of the floor materials.

(*c*) *The relations between thermal sensation, skin temperature and air temperature*

For the two subjects taken together, a decrease of 10° F. in the air temperature, from 65 to 55° F., decreases the mean final skin temperature by 10·9° F. on the ankle, and 12·5° F. on the toes (Tables 3 and 4). Assuming a linear relationship between skin and air temperature over this limited range, one degree increase in air temperature causes 1·1° F. increase in the temperature on the ankle and 1·3° F. increase on the toe. The more distal region again shows the greater change.

Comparing the mean final value for sensation on the ankle after 60 min. at 55° F. (Tables 1 and 2) with the corresponding values at 65° F. the difference is seen to be 2·0 units. The change of skin temperature under the same circumstances is 10·9° F. Thus, a change of one unit in sensation is associated with a change of 5·5° F. in ankle temperature. The corresponding change of temperature is slightly greater for the more distal regions, being 6·3° F. for the toe and 6·2° F. for the sole.

It would be very useful for an objective assessment of thermal comfort if, in fact, a high degree

Table 5. *Using the combined data of the two subjects there is shown the statistical significance of the differences between the mean changes in skin temperature and thermal sensation, when the feet are on cork and concrete for* 60 *min. at an air temperature of* 55° F.

	Sole		Ankle		Toe	
	Temperature	Sensation	Temperature	Sensation	Temperature	Sensation
			Concrete			
No. of observations	8	8	8	8	8	8
Mean change	9·16° F.	1·63 units	4·48° F.	1·25 units	8·28° F.	1·75 units
(S.D.)²	11·31	0·48	11·07	0·69	5·87	0·44
S.D.	3·36° F.	0·70 units	3·33° F.	0·83 units	2·42° F.	0·66 units
			Cork			
No. of observations	10	10	10	10	10	9
Mean change	2·42° F.	1·20 units	3·42° F.	1·30 units	5·20° F.	1·11 units
(S.D.)²	16·01	0·56	22·68	0·41	28·38	0·97
S.D.	4·0 ° F.	0·75 units	4·76° F.	0·64 units	5·33° F.	0·98 units
'*t*'	3·59	1·17	—	—	1·39	1·46
P	$>0\cdot01$	$<0\cdot10$	—	—	$<0\cdot10$	$<0\cdot10$
	Highly significant	Not significant	Not significant	Not significant	Not significant	Not significant

of correlation were found to exist between skin temperature and sensation of warmth. The statistical association of the two variables was worked out separately for each subject at the two air temperatures. The values of the correlation and regression coefficients are shown in Table 6 for subject 1 and Table 7 for subject 2. Also shown in the Tables are the skin temperatures calculated from the regression equations with sensation equal to zero, i.e. the comfortable condition, and the change in skin temperature associated with a change of one unit of sensation on the different regions of the foot.

Significant positive correlations between skin temperature and the warmth sensation on every region of the foot were found for each subject, with one exception, viz. the ankle at 55° F. air temperature in subject 1. The degree of association in general is somewhat higher for subject 2 than for subject 1, but with neither subject are the correlation coefficients high enough to enable a person's

Table 6. *The correlation of skin temperature and feeling of warmth in subject* 1 *when shod, and in the room at air temperatures of* 55 *and* 65° F.

(r = coefficient of correlation; S.E. = standard error; S.D. = standard deviation; a and b are the constants of the regresssion equation $S = at + b$, where S is sensation and t is skin temperature)

Region	Sole		Toe		Ankle	
Room temp. (° F.)	55	65	55	65	55	65
No. of obs.	109	100	112	64	124	84
r	+0·59	+0·62	+0·39	+0·60	+0·003	+0·45
S.E.	±0·06	±0·06	±0·08	±0·08	—	±0·09
a	0·122	0·105	0·007	0·109	—	0·130
b	−10·02	−8·85	−6·03	−8·38	—	−10·08
Mean skin temp. (° F.)	78·0	86·3	80·6	87·6	79·1	86·1
S.D. (° F.)	4·9	4·9	4·5	4·1	—	2·6
Mean sensation	−0·5	+1·2	−0·7	+1·2	−0·7	+1·1
S.D. (units)	1·0	0·8	0·7	0·7	—	0·8
Skin temp. (° F.) where:						
$S=0$	82·1	84·3	91·4	76·9	—	77·4
$S=-1$	73·9	74·8	76·2	67·8	—	69·6
Change in skin temp. for one unit of sensation	8·2	9·5	15·2	9·1	—	7·8

Table 7. *The correlation of skin temperature and feeling of warmth in subject* 2 *when shod, and in the room at air temperatures of* 55 *and* 65° F.

(r = coefficient of correlation; S.E. = standard error; S.D. = standard deviation; a and b are the constants of the regression equation $S = at + b$.)

Region	Sole		Toe		Ankle	
Room temp. (° F.)	55	65	55	65	55	65
No. of obs.	115	54	108	40	110	41
r	+0·68	+0·77	+0·69	+0·66	+0·62	+0·39
S.E.	±0·04	±0·06	±0·05	±0·09	±0·08	±0·06
a	0·128	0·20	0·135	0·158	0·149	0·203
b	−8·94	−15·79	−10·26	−12·40	−11·34	−15·64
Mean skin temp. (° F.)	64·2	79·0	67·5	80·4	68·0	79·5
S.D. (° F.)	5·6	3·9	5·0	4·4	3·6	2·2
Mean sensation	−0·7	+0·3	−1·1	+0·3	−1·1	+0·5
S.D. (units)	1·0	1·0	1·0	1·1	0·9	1·2
Skin temp. (° F.) where:						
$S=0$	69·8	79·0	76·0	78·5	76·1	77·0
$S=-1$	62·0	74·0	68·6	72·1	69·3	72·1
Change in skin temp. for one unit of sensation	7·8	5·0	7·4	6·4	6·8	4·9

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sensation of warmth to be predicted accurately from a knowledge of his skin temperature. In both subjects the region showing the highest correlations is the sole (the most distal part), whilst the lowest correlations were found with the ankle.

The regression coefficients are dissimilar not only for the two subjects, but also for the different regions on the same subject. They also differ in the same subject at the two air temperatures. When, however, the skin temperatures at which subject 2 was entirely comfortable ($S=0$) are calculated from may occur on any region before discomfort is felt there differs according to subjects and conditions. If the ranges are compared at 55 and 65° F., subject 2 is seen to have consistently higher ranges at the lower temperature. This relationship is not apparent in subject 1. In round figures, the average change in skin temperature required for one unit change of sensation is 10·0° F. for subject 1, and 6·4° F. for subject 2. Considerable changes in skin temperature can occur on the feet before discomfort occurs.

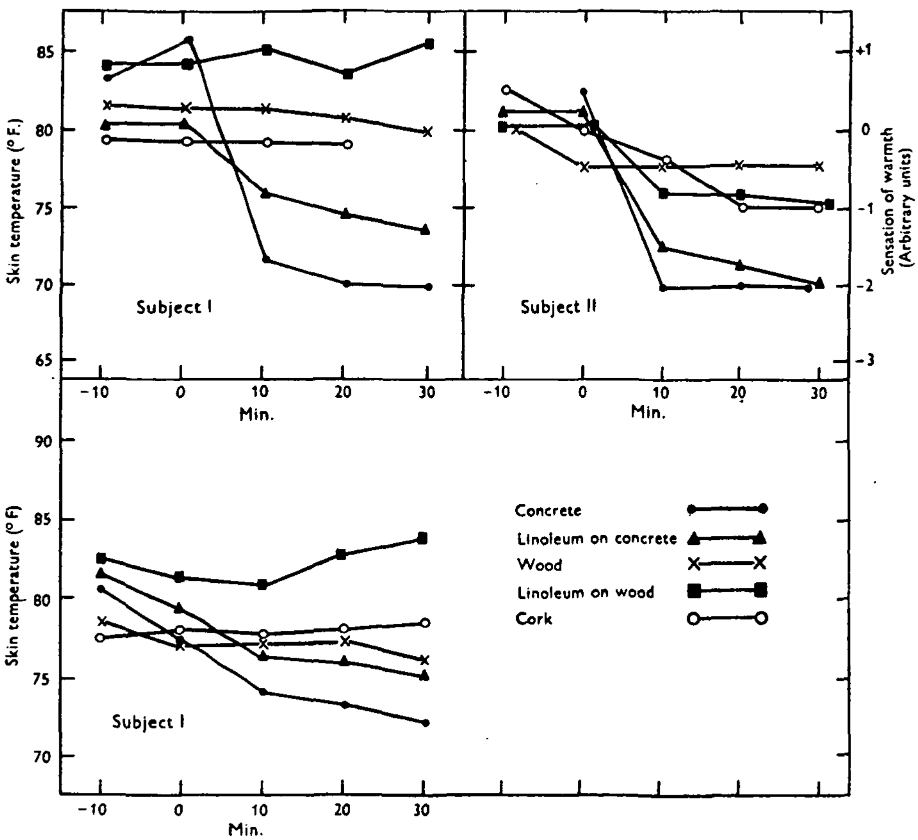

Fig. 3. Sensations of warmth and skin temperature (° F.) of the sole of the bare foot plotted against time (minutes) of contact with different materials at a room temperature of 65° F.

the appropriate equations, very similar values are found at the two room temperatures, and for each region of skin with but one exception (Table 7). No such consistency is shown in the values for subject 1 (Table 6). The point of similarity between the subjects seems to be the requirement of practically identical ankle temperatures for comfort, viz. 77·0 and 77·4° F. It is also shown that subject 1 requires higher sole temperatures for comfort than subject 2, viz. 12·3° F. higher at 55° F. and 5·3° F. higher at 65° F. air temperature.

The extent of the change in skin temperature that

(2) *Bare feet*

(*a*) *The effect of various floor materials on the comfort of the bare feet*

The main object in carrying out these tests was to determine quantitatively the change in skin temperature and sensation that can occur with the feet in contact with various materials. It was further hoped to provide data showing how far a thin insulating layer on a basal layer of concrete will serve to diminish the chilling effect of the concrete. The results with the different flooring materials are

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given in Tables 8 and 9. The values shown are the skin temperatures and the thermal sensation of the bare foot after 30 min. contact with the floor surface. Fig. 3 illustrates the temperatures and sensations on the sole of the foot at various times after contact with the floor at 65° F.

A comparison of the temperature changes of the sole in both subjects (Table 8) provides conclusions which might be expected from a knowledge of the thermal conductivities of the materials in the case of cork, concrete and wood. It is interesting to compare these materials when each is covered with a single layer of good-quality linoleum. With neither linoleum on cork nor linoleum on wood are the relative changes in sole temperatures appreciably different from cork alone. With linoleum over concrete the fall in sole temperature is much greater than with either cork or wood covered with linoleum and is only less than on bare concrete. Fig. 3 shows the speed at which the chilling of the feet, caused by the basal layer of concrete, takes effect. The fall in temperature is not nearly so rapid as with bare concrete but the difference, in comparison with the linoleum on cork, shows that the factor operating is not the linoleum but the basal layer. A similar series of changes is indicated on a graph of thermal sensation plotted against time of contact (Fig. 3).

It is apparent from the preceding tests, that to prepare a floor based on concrete which will chill the bare feet no more than does wood it is necessary to provide a covering layer which is superior to ordinary linoleum as an insulator.

Table 8. *The skin temperatures of the two subjects have been combined and the initial and final mean values are given together with the changes of sensation occurring after sitting for 30 min. with the bare feet on different flooring materials in the room at 65° F. air temperature*

	Skin temperatures (° F.) on		Change of sole temp. relative to change in ankle temp.
	Sole	Ankle	
Concrete:			
Initial	81·5	84·0	
Final	71·1	80·4	
Change	10·4	3·6	−6·8
Linoleum on concrete:			
Initial	79·7	81·9	
Final	74·3	79·6	
Change	5·4	2·3	−3·1
Wood:			
Initial	79·3	82·3	
Final	78·1	79·3	
Change	1·2	3·0	+1·8
Linoleum on wood:			
Initial	83·1	83·6	
Final	84·9	81·4	
Change	−1·8	2·2	+4·0
Cork:			
Initial	78·3	83·8	
Final	77·3	79·0	
Change	1·0	4·8	+3·8
Linoleum on cork (subject 1 only):			
Initial	82·9	86·1	
Final	80·5	80·5	
Change	2·4	5·6	+3·2

Table 9. *The warmth votes of the two subjects have been combined and the initial and final mean values are given, together with the changes occurring after sitting for 30 min. with the bare feet on different flooring materials in the room at 65° F. air temperature*

	Sensations of warmth on	
	Sole	Ankle
Concrete:		
Initial	0·4	0·4
Final	−1·9	−1·3
Change	2·3	1·7
Linoleum on concrete:		
Initial	0·2	0·2
Final	−1·3	0·0
Change	1·5	0·2
Wood:		
Initial	0·0	0·0
Final	0·0	−0·8
Change	0·0	0·8
Linoleum on wood:		
Initial	0·3	−0·1
Final	−0·2	−1·0
Change	0·5	0·9
Cork:		
Initial	0·0	−0·8
Final	−0·7	−1·1
Change	0·7	0·3
Linoleum on cork (subject 1 only):		
Initial	0·0	0·0
Final	−1·0	−1·5
Change	1·0	1·5

(b) *Correlations of skin temperature and sensation*

The correlation data are given in Tables 10 and 11 and refer to observations made at an air temperature of 65° F. At 55° F. the changes in sensation, especially on the sole, were so precipitate that their assessment in relation to the simultaneously rapid changes in skin temperature became very unreliable. At 65° F. the correlation coefficients were significant only for the sole and toe regions in the two subjects, and the coefficients were somewhat smaller in magnitude than in the tests with shod feet. When the regression coefficients are compared for the same regions and for the same air tempera-

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tures, considerable differences are found between shod and bare feet. In other words, similar values of skin temperature at a particular region on the extremity with the feet bare and with the feet shod represent different thermal sensations when the values of these are calculated from the appropriate equations. If, for instance, the foot is comfortable at a given skin temperature when shod, it will feel cooler at the same temperature when bare. For equivalent sensations of comfort on bare feet, subject 1 requires the sole to be 8·6° F. higher and the toes 19·1° F. higher than when shod! In subject 2 the sole must be 2·4° F. higher and the toes 9·8° F. higher when bare than when shod.

Table 10. *The correlation of skin temperature and feeling of warmth in subject* 1 *with bare feet, in the room at* 65° F.

(r = coefficient of correlation; S.E. = standard error; S.D. = standard deviation. a and b are the constants of the regression equation $S=at+b$, where S is sensation and t is skin temperature.)

Region	Sole	Toe
Room temp. (° F.)	65° F.	65° F.
No. of obs.	60	51
r	+0·53	+0·53
S.E.	±0·09	±0·10
a	+0·094	+0·087
b	−8·73	−8·35
Mean skin temp. (° F.)	79·2 °F.	80·9° F.
S.D.	5·1° F.	4·3° F.
Mean sensation	−1·3 units	−1·3 units
S.D.	0·9 units	0·7 units
Skin temp. (° F.) where:		
$S=0$	92·9	96·0
$S=-1$	82·2	84·5
Change in skin temp. required to give 1 unit change of sensation	10·7	11·5

The two subjects agree in a general way in their requirement of a higher skin temperature with bare feet for equivalent comfort. They agree very closely in their tolerance range at this level, namely that a 10° F. change in skin temperature is required for one arbitrary unit change in sensation; and this range is the same as that when the feet are shod.

(3) *The effect of air movement on the thermal sensation and the temperature of the shod feet*

The air movement in the controlled temperature room during the previous tests never exceeded 20 ft./min. and averaged about 10 ft./min. To provide a fuller description of the environmental factors affecting the warmth of the feet, and to show the relative importance of some of the factors, a series of tests was done with air at the temperature of the room, namely 55° F., and moving across the feet at velocities from 50 to 200 ft./min. A few tests were done with air issuing from a duct at 150 ft./min., and 7° F. cooler than room air.

Similar trends were observed in both subjects, and therefore the data have been combined in a series of composite curves showing the effect of increasing air velocities. The results show that air velocities up to about 50 ft./min., provided that they are at a similar temperature to the room air, have little effect in reducing the time interval which elapses before the onset of discomfort. Looking at the results in another way, after 60 min. exposure

Table 11. *The correlation of skin temperature and feeling of warmth in subject* 2 *with bare feet, in the room at* 65° F.

(r = coefficient of correlation; S.E. = standard error; S.D. = standard deviation. a and b are the constants of the regression equation $S=at+b$, where S is sensation and t is skin temperature.)

Region	Sole	Toe
Room temp. (° F.)	65° F.	65° F.
No. of obs.	61	46
r	+0·44	+0·68
S.E.	±0·09	±0·07
a	+0·092	+0·107
b	−7·49	−9·45
Mean skin temp. (° F.)	76·6° F.	77·5° F.
S.D.	5·7° F.	5·1° F.
Mean sensation	−0·4 units	−1·2 units
S.D.	1·2 units	0·8 units
Skin temp. (° F.) where:		
$S=0$	81·4	88·3
$S=-1$	70·6	79·0
Change in skin temp. required to give 1 unit change of sensation	10·8	9·3

to a draught of 50 ft./min., the drop in sensation is only 0·5 units greater than in still air, although, of course, the drop has been to the level of chilling, namely −1·5 to −2·0 on the sensation scale. In a similar period, the higher velocities would take the feet to the −3 level of sensation. From this it may be concluded that the dominant factor affecting the thermal sensation of the shod feet, with air velocities up to 50 ft./min., is the air temperature. Fig. 5 shows tolerance times, i.e. the time required for the foot to become 'too cool' (−2·0), plotted against the air velocity.

If a demonstrable effect of draught is not apparent at 55° F. it is unlikely to appear at 65° F. On the other hand, at temperatures below 55° F., the effects of localized air movement are more striking. The curve for 140 ft./min., in Fig. 4, is based on tests done with air issuing from the duct at 48° F. when the room air was 55° F. It appears that this curve, over the initial part of its course, is at least as steep as the curve for air at 55° F. but with a speed of 200 ft./min.

The shapes of the temperature curves at different air velocities (Fig. 4) are very different from the corresponding sensation curves. In the first 10 min. after turning on the fan, and during the period of observation before then, the skin temperature rises rapidly, whilst the foot feels cooler. After 10 min., a fall in skin temperature becomes associated with an increased feeling of chilliness. Inspection of

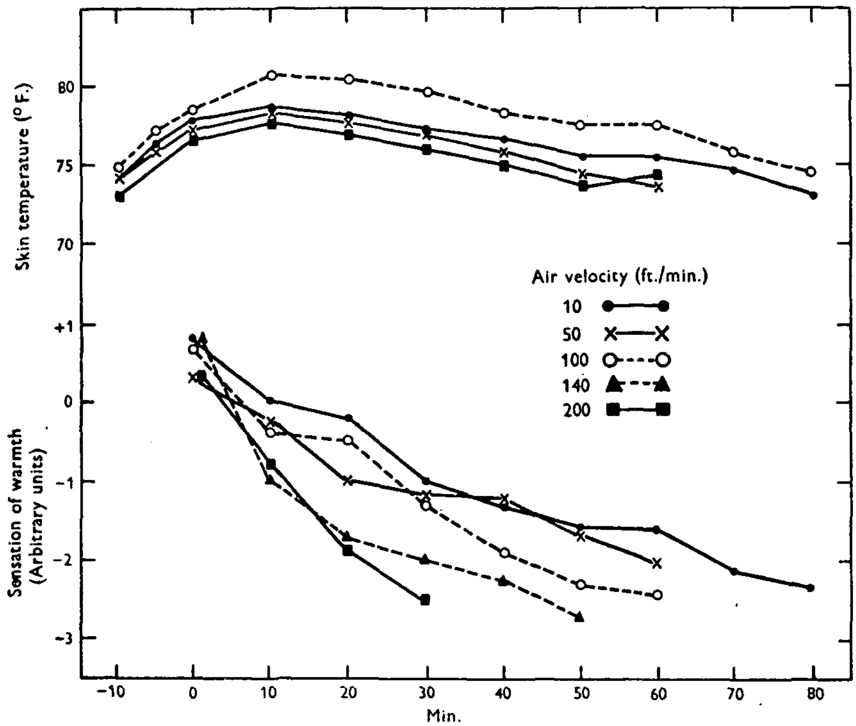

Fig. 4. Sensations of warmth and skin temperatures (mean values for the whole foot) of the shod feet of subjects 1 and 2, plotted against time of exposure of the foot to different wind speeds. The 140 ft./min. line represents tests with air 7° F. lower than room air temperature (55° F.) moving over the feet.

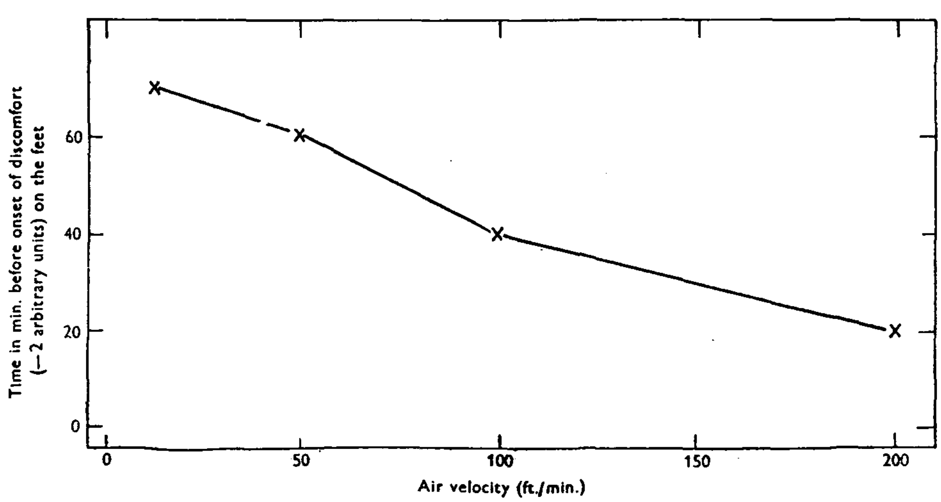

Fig. 5. Time in minutes elapsing before the foot becomes too cool plotted against the speed of the air moving across the foot at a room temperature of 55° F.

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Fig. 4 shows that there is apparently little relation between rate of fall of skin temperature and rate of air movement. When the data for velocities of 10 ft. and 200 ft./min. are compared, it is seen that the time required for the feet to reach the same skin temperature, i.e. 74° F. is only 20 min. longer in the second instance than in the first, but when the time required to reach the same degree of discomfort is compared, the difference is 50 min. This is a further illustration that under certain conditions there is little association between skin temperature and thermal sensation.

(4) *Changes in skin temperature during the test period*

Fig. 4 shows that a rise in skin temperature occurred initially in every test where air velocity was considered. A similar though less pronounced rise was found for subject 1 in a number of the tests on flooring materials. Also to be noted is the steady fall in sensation over the same period (Fig. 4).

It will be appreciated that, for the purpose of comparing the effects of different conditions on the feet, it was necessary to start the experiments with the feet always at about the same level of thermal sensation, a value of zero on the arbitrary scale of warmth, i.e. 'comfortable', being aimed at. The feet were often so cold, however, that difficulty was experienced in warming them, and the remedy adopted was to go for a walk outside for 10 min. at a moderate pace. The consequence of this slight activity was to warm the feet, but incidentally it also appeared to introduce a phase of rapid and pronounced change in the skin temperature of the foot generally. A fall in skin temperature in one foot usually was followed by a rise in skin temperature of 6–8° F. after sitting down following the exercise.

Fig. 6 illustrates an experiment made specifically to test under what circumstances these fluctuations occur. The ankle temperature of subject 1 at the beginning of the test was 85° F. He then left the test room, which was at 55° F., went outside where the shade temperature was about 80° F. and proceeded to walk in the open air at a moderate pace for about 10–15 min. Immediately on return, his ankle temperature was measured by means of a thermocouple already in position, and the skin temperature was found to have dropped during the walk to 73° F. Frequent measurements were then made during the next 10 min. with the subject seated in the controlled-temperature room and a steady rise amounting to 7° F. in the temperature of the ankle was noted in the 10 min. The subject then walked across the grounds to another building, 200 yards away, remained there for 30 min., and then returned and sat down. His ankle temperature was then observed to rise from 74 to 86° F. in 14 min. On this occasion the measurements were made in a room at 75° F. From the above, it would appear that there occurs:

(1) A considerable fall in the temperature of the ankle during walking, when the initial temperature of the skin and the temperature of the outside air are both high.

(2) A rapid rise in skin temperature on sitting down again whether in a cold room or a warm one

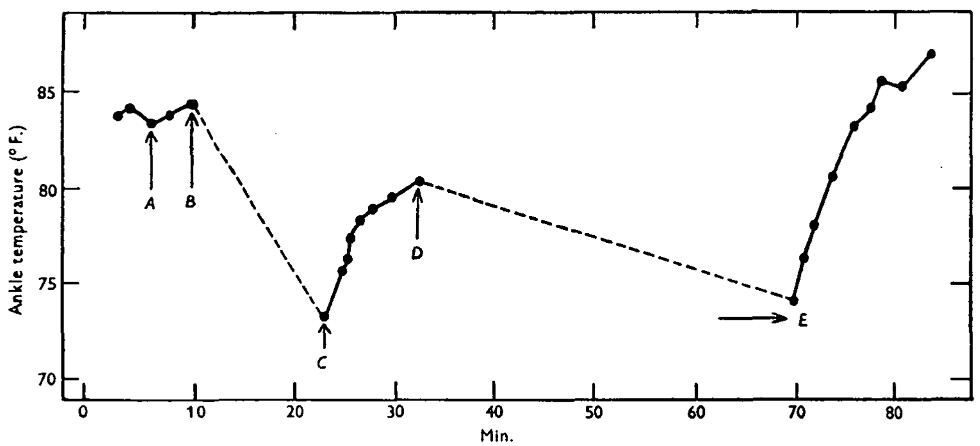

Fig. 6. The ankle temperatures (° F.) of subject 1, taken whilst sitting before and after exercise plotted against time in minutes. (*A*) Subject stands up. (*B*) Subject begins walk. (*C*) Subject sits at 55° F. (*D*) Subject walks to building 200 yards distant. (*E*) Subject has walked back and sat down in room at 75° F.

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IV. DISCUSSION

Considering first the changes in sensation which were found to occur under the various circumstances, the factor most influencing comfort in every case is the environmental air temperature. This is so whether effects of draught on the feet or the conductivities of different floor surfaces are under examination. When a person wearing shoes is seated, provided that the air temperature is 65° F. and the temperature conditions uniform, it is unlikely that either a concrete floor or a draught up to 50 ft./min. will cause discomfort. But it is important to emphasize that this conclusion only applies to a test period lasting 60 min. An air temperature of 55° F., however, was sufficient of itself to cause a change in the feelings of warmth of the feet which was at least as great as that due to flooring materials or moderate air movement. The temperature data in Table 1, taken in conjunction with the calculated change in skin temperature, required to produce one unit change in sensation (Tables 6 and 7) support the above statement since they show that discomfort was not produced by a concrete floor at 55° F. when the test was begun with the feet comfortable and the period of exposure 60 min. However, the results imply that if one sits for longer than an hour with the shod feet in contact with bare concrete, discomfort of the feet will be experienced, whereas on cork the feet will be reasonably comfortable, so that a cork floor will generally be more comfortable.

If concrete is being considered for the floors of bedrooms it is important to know whether undesirable chilling of bare feet can be prevented by covering the concrete with a thin layer of insulating material. The experiments show that ordinary linoleum over concrete does not afford much protection. As Fig. 3 shows, the basal layer of concrete begins to affect the foot within a short time. This effect is apparent at 65° F., which is usually regarded in this country as above the optimum temperature for a bedroom, and it is clear that the concrete layer will have a greater effect at 55° F.

However, any calculations based on skin temperature must be treated with caution, and the ultimate criterion must be that of sensation. The investigation described in the preceding text indicates that too much reliance should not be placed on skin temperature for the prediction of a particular person's sensations of warmth, even when the environmental conditions are strictly defined. This is clear from the magnitude of the correlation coefficients, the highest of which—that for the sole of one subject—is $+0{\cdot}77$, whereas in the other subject the correlation between sensation and the temperature of the ankle was insignificant. The regression equations differ for different regions on the foot, and they also differ in the same subject, even for the same region, according to whether the foot is bare or covered. In other words, it is possible to have the same temperature on, say, the ankle, associated with entirely different sensations of warmth according to the circumstances. Bazett & McGlone (1927) and later Nielsen (1947) have suggested that sensations of warmth may correspond more closely to the steepness of the temperature gradient in the skin than to skin surface temperature.

In some tests, particularly where air movement was being examined, there was an initial phase when the skin temperature was rising whilst the foot felt progressively cooler. Bazett & McGlone (1927) noted a similar effect after sea bathing, viz. intense sensations of cold accompanying a rapidly rising skin temperature. In our tests this inverse relation between temperature and sensation seemed to be associated with some degree of activity before the tests began. Associated with the phenomenon was a pronounced fall in skin temperature illustrated in Fig. 6, when the subject was walking. There is the possibility that the fall in temperature might have been caused by air movement over the limb, since walking at a rate of 4 miles/hr. corresponds to a relative air movement across the body of 350 ft./min. But this explanation is unlikely, for the following reasons. Rapid changes in skin temperature of this magnitude did not occur in our experiments when the subjects were sitting, even at 55° F. (Fig. 4). The region on the foot where the fall in temperature was observed was trebly protected by the shoe, the sock, and the cloth of the trousers.

A possible explanation is that the requirement for blood within the tissues during activity, may lead to a draining of the superficial tissues of the limb and therefore to cooling of the surface. When the subject sits down again two factors may operate. There is diminution in heat production which may reduce the central blood requirement and thus increase the peripheral supply. Venous stasis will be encouraged by diminution of the normal massaging action of the muscles on the blood vessels, and this may induce a temporary rise in skin temperature. When one sits down after the exercise, heat may still be accumulating in the limb, since its skin temperature is low and the heat loss may not exceed the heat produced within the limb or conveyed to it. Hence the initial sensation of warmth. Very soon, however, the heat inflow to the limb diminishes and simultaneously, for the reasons already given, the skin temperature rises, so that heat no longer accumulates at the previous rate, and the sensation of warmth progressively diminishes. Finally, heat dissipation exceeds heat inflow and a progressive fall in skin temperature becomes