

## THERMAL COMFORT IN WARM AND HUMID ATMOSPHERES

OBSERVATIONS ON GROUPS AND INDIVIDUALS IN SINGAPORE

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(With 6 Figures in the Text)

Investigations carried out in warships in the tropics and experimental studies suggest that, in warm climates, ventilation standards based on comfort criteria will usually provide light or sedentary workers with a thermal environment in which their working efficiency will not be impaired (Ellis, 1952). In temperate climates women usually prefer rather warmer conditions than men (Bedford, 1948), a preference which Yaglou & Messer (1941) attribute to differences in clothing, and it has been suggested that the desirable levels of warmth may vary for different races. Men and women of European and Asian extraction were therefore included in a survey which was carried out during 1951 and 1952 to determine the comfortable levels of warmth for 'acclimatized' British men engaged in light indoor occupations on shore in Singapore.

Most contemporary views on desirable and acceptable levels of warmth for human activities have been derived from the study of groups. The subjects who took part in this investigation were asked to record their 'comfort votes' and the prevailing temperature conditions for several weeks or months so that inter- and intra-individual variability might also be examined.

### METHODS

#### *Subjects*

The subjects of European extraction (referred to here as 'Europeans') were twenty-one adult men and thirteen women from the United Kingdom or Australia who had resided in Singapore for at least 6 months but not more than 2½ years. The majority were members of the staff of the Royal Naval Tropical Research Unit and their wives. The rest were either naval officers, naval officers' wives, or senior ratings living on shore in Singapore. The average age of the men was 30 and of the women 34 years. They recorded their comfort votes whilst engaged in light or sedentary occupations indoors in their homes or offices.

For the first experiment the Asian subjects were men and women medical students. Comfort votes were recorded before and after physiology lectures. There were 67 Chinese, 6 North Indian, 5 South Indian, 11 Ceylonese, 10 Malay and 3 Eurasian men students and the women comprised 10 Chinese, 2 South Indian,

2 Ceylonese, 1 Malay and 1 Eurasian. Their average age was 22 years. The range of temperature conditions during the morning when these lectures took place was too narrow to enable an adequate survey to be carried out.

For later experiments Asians on the staffs of the Unit, the Medical School and the Royal Naval Health Office and their wives, acted as subjects. The men were 10 Chinese, 2 Eurasians, 1 Indian and 1 Malay, their average age being 34; and the women were 1 Eurasian and 8 Chinese, their average age being 25. These Asians had lived in the tropics all their lives, with the exception of two men who had spent short periods in England but returned to Singapore more than 6 months before the investigation began. Most of the votes were recorded whilst they were engaged in sedentary occupations at the Unit or in the University, but some votes were recorded in their homes. All the Asians wore light clothing similar to that worn by the Europeans when recording their votes.

#### *Procedure*

Most of the Europeans and about half the Asians (apart from the students) recorded their comfort votes and the air temperatures themselves. They were each provided with about 100 comfort vote slips (Table 1), a sling hygrometer, a bottle of distilled water, a pipette for topping up the water reservoir of the wet-bulb thermometer, and printed notes which included advice on the use of the sling hygrometer. The Asians who were unfamiliar with this instrument were visited in their offices or work-places by a technician who distributed comfort vote slips and, while these were completed, recorded the dry- and wet-bulb temperatures. The air temperatures for some of the European women were recorded by their husbands. When the students recorded their comfort votes an observer measured the air temperatures in eight different positions in the lecture theatre, and the mean dry- and wet-bulb temperatures were ascertained. Thus all the temperature measurements were made by persons who knew how to use the sling hygrometer.

The coding of the comfort sensations was that adopted by Bedford (1936, 1948). The information requested on the state of the skin was used to estimate whether or not a person was beginning to sweat.

Effective temperatures (Houghten and Yaglou, 1923, 1924; Yaglou & Miller, 1925) were determined from the normal chart which accompanies the Medical Research Council's War Memorandum No. 17 (Bedford, 1946), and for this purpose it was assumed that when the subject reported the air movement to be 'still', 'slight', 'moderate' or 'very good' the corresponding air velocities were 20, 100, 200 and 400 ft./min. respectively. These arbitrary values were assigned because it had been observed previously in warships in tropical waters and in the wind tunnel of this laboratory that, at the levels of warmth covered by this survey, air movement is rarely perceptible to a lightly clothed observer when the mean recorded air velocity about the observer is much below 100 ft./min., which confirms Baetjer's (1924) observation that whereas air currents of 30 ft./min. are noticeable when the air temperature is 54° F., velocities lower than 120 ft./min. may not be perceived when it is raised to 86° F. When the average air velocity is about 200 ft./min. air movement is usually easily perceptible, and above 300 ft./min. it is markedly

perceptible. The air velocity of 20 ft./min. was probably on the low side, as most of the subjects who reported still air would have been exposed to rather greater air currents than this, but it was convenient to use this figure and the margin of error with the normal chart amounted only to fractions of a degree. 'Very good' air movement was not often reported.

Table 1.

THE COMFORT VOTE SLIP								
D.B.      ° F.		W.B.      ° F.			E.T.      ° F.			
Date		Time			Place			
		Sensation of comfort						
		*MTW	TW	CW	C	CC	TC	MTC
Air movement perceived	Nil							
	Slight							
	Mod.							
	V. Good							

The skin of my face is †wet clammy‡ dry  
 „ „ neck „ wet clammy dry  
 „ „ arms§ „ wet clammy dry  
 „ „ waist „ wet clammy dry  
 „ „ seat „ wet clammy dry

† Cross out the terms which do *not* apply

- \* MTW = much too warm;      TW = too warm;  
 CW = comfortably warm;      C = comfortable;  
 CC = comfortably cool;      TC = too cool;  
 MTC = much too cool.

‡ Clammy refers to the intermediate state of the skin, and the associated sensation of comfort which is experienced, when it cannot be asserted that the skin or clothing is wet, and yet it would be wrong to describe it as dry. In other words when sensible perspiration has commenced but is not yet so profuse that it can be identified as 'wetness'. 'Sticky' or 'damp' might be alternative descriptive terms.

§ 'Arms' does not include the axillae (or armpits); only the forearm and upper arm.

The instructions to the subjects stated: 'It does not matter when or where the temperature measurements are made and the votes are recorded provided that the situation is indoors (it is important to exclude the effect of sunlight), not near to any obvious sources of radiant heat (such as a cooking stove), that the observer has not been engaged in strenuous physical exertion within the previous hour, and is not engaged in a strenuous occupation at the time of recording the vote. The

observers may be either seated or standing. The most convenient and useful range of temperature conditions to investigate is: early morning, before or after breakfast, before lunch, early afternoon, early evening and before going to bed. As a general principle at least one hour should be allowed to elapse between the different occasions when temperature measurements are made and comfort votes are recorded. Record your comfort vote *before* whirling the sling hygrometer. Read temperatures to the nearest degree Fahrenheit. Observers should *not* refer to their previous votes in order to see if they recorded a similar vote for a similar temperature. The space marked "E.T." should be left blank. The "Place" should be indicated briefly, e.g. bedroom, living room, office, laboratory. Remarks should be entered on the back of the comfort vote slip. It is assumed that the men will be wearing shirts and shorts or slacks, and that the women will wear light frocks. If a man should be wearing a coat, or if a woman should wear a long dress or a woollen cardigan, or if the voter has completed a vigorous game, such as football, within the previous few hours this should be mentioned. Observers are to discard their first 10 slips so that this can be used as a practice period.'

#### RESULTS

The shortest time for a subject to complete 100 slips was about 1 month and the longest time about 4 months. On the average 102 comfort slips were completed by each of the fifty-seven individual subjects. The following account refers to these votes except where it is stated otherwise. Three of the European women subjects recorded two sets of votes at an interval of approximately 8 months. As one of them was a cold-sensitive person, another was warmth-sensitive and the third was average in this respect, it is not thought that this resulted in an unfair bias, and it was a useful addition to the number of reliable opinions. In addition, the students completed a total of 2111 slips before and after their lectures.

#### *Comfortable levels of warmth for Europeans and Asians*

The total comfort votes recorded by European and Asian men and women were sorted to determine the percentages of votes recorded which stated that the voter was 'comfortable' for each 1° F. rise in effective, dry- and wet-bulb temperatures. Three facts are apparent from Fig. 1. First, the more uniform curves obtained in relation to effective temperature indicate the value of using a scale which incorporates the effects of air temperature, humidity and air movement, rather than measurements of air temperature alone. Secondly, 56% was the highest proportion of 'comfortable' votes recorded at any one level of effective temperature. Thirdly, although the largest proportions of comfortable votes were recorded by European men and women and by Asian men when the effective temperature was between 76 and 76.9° F., there was very little variation between 75 and 78° F. for European men or between 73 and 78° F. for European women.

In order to identify the optimum levels of warmth with greater accuracy, the votes were re-sorted in relation to effective dry- and wet-bulb temperatures to determine the relative percentages of 'reasonably comfortable' votes (comfortably

warm, comfortable or comfortably cool), of 'cool' (comfortably cool, too cool, or much too cool) as opposed to 'warm' (comfortably warm, too warm or much too warm) votes, and of votes which reported wetness or clamminess of the skin at any one of the positions named on the comfort slip. These relationships are shown in Figs. 2A, B and C for European men and women. The more uniform curves obtained

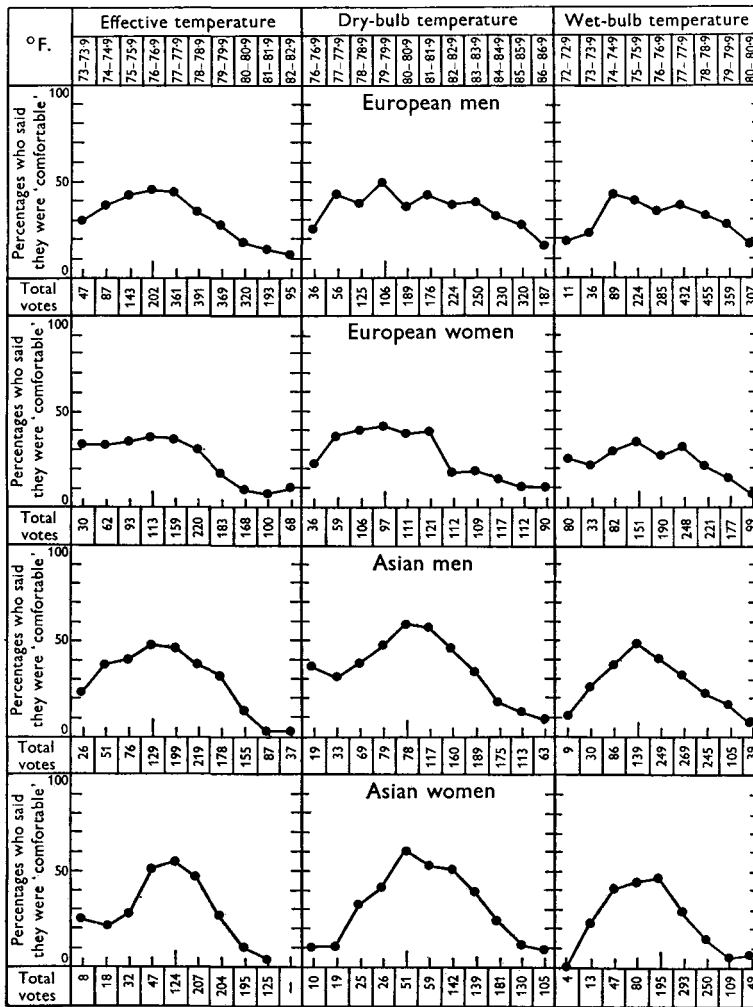


Fig. 1. Relation between votes recorded by European men and women and Asian men and women who were 'comfortable' and 1° F. variations in effective dry- and wet-bulb temperature.

in relation to effective temperature again support its claim to be a comprehensive index for gauging the relative comfort of sedentary people under warm thermal conditions. The levels of warmth at which the maximum numbers of 'reasonably comfortable' votes and approximately equal numbers of 'cool' and 'warm' votes were recorded are in close agreement. Under these conditions practically no one reported that his skin was wet with perspiration and very few felt clammy.

The association between the rise in the proportions of votes reporting wet or wet and clammy skin and 'warm' votes, and the decrease in 'cool' and 'comfortable' votes indicates that the onset of sweating may have contributed considerably to the onset of thermal discomfort for these lightly clothed sedentary persons.

Graphs constructed for the Asian men and women revealed similar characteristics. The 'desirable' or 'optimum' levels of warmth for the four groups, defined as the levels at which equal proportions of cool and warm votes were recorded, are shown

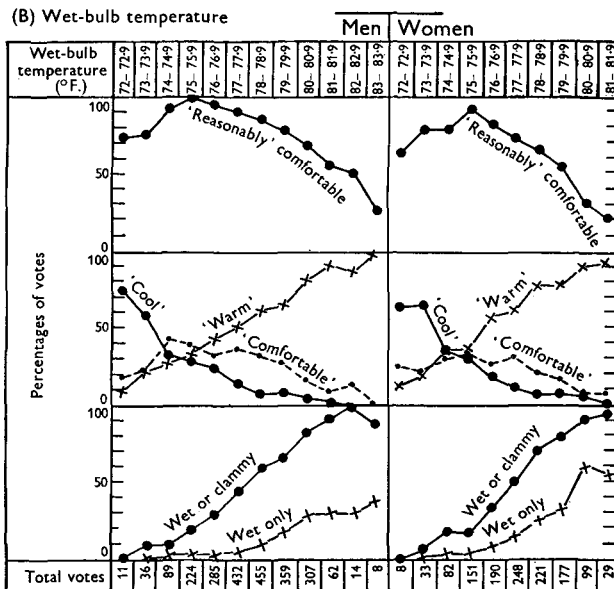
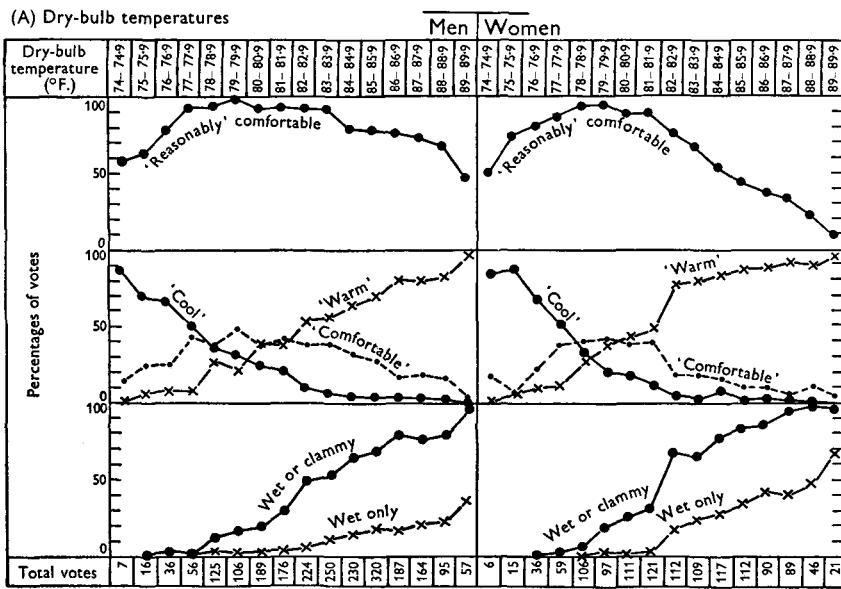


Fig. 2. For description see p. 392.

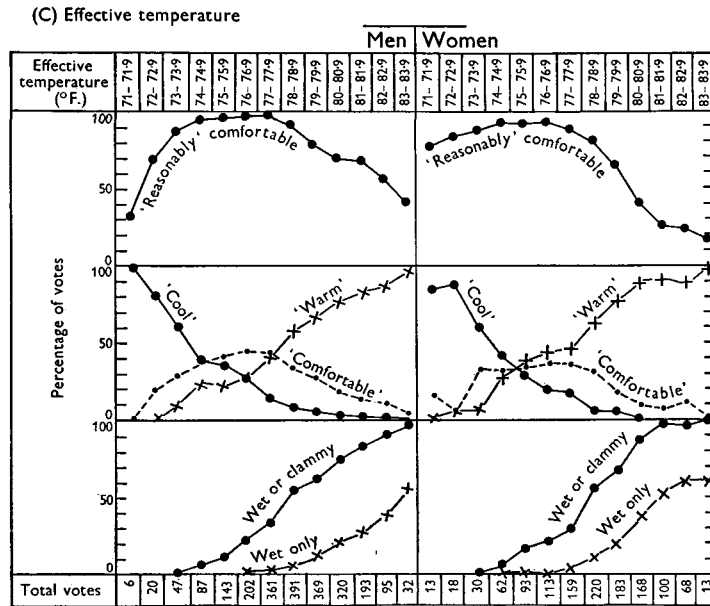


Fig. 2. Comfort and sweating for European men and women at various levels of warmth.

Table 2. 'Desirable' levels of warmth for groups of European (E.) and Asian (A.) men and women in Singapore

Approximately equal numbers of 'cool' and 'warm' votes were recorded when the temperature was:	Dry-bulb temp. (° F.)		Wet-bulb temp. (° F.)		Effective temp. (° F.)	
	Men	Women	Men	Women	Men	Women
	E.	79-79.9	78-78.9	74-74.9	74-74.9	76-76.9
A.	80-80.9	81-81.9	75-75.9	75-75.9	75-75.9	77-77.9

in Table 2. This level varies between effective temperatures of 74 and 78° F. for European women, Asian men, European men and Asian women respectively; but Fig. 2C shows that the great majority of European men and women were reasonably comfortable within this range. The rather warmer condition preferred by the Asian women was probably partly due to the fact that they were the most sedentary group.

The 'acceptable' levels of warmth, defined as the levels below or above which more than 80% of votes were recorded in the comfort zone or below which less than 20% of voters recorded that their skin was wet with perspiration, are shown in Table 3. When more than 80% of voters were reasonably comfortable very few of them were wet with sweat. The levels of warmth at which less than 20% of European men were sweating accords well with the observation of Behnke, Pace & Consolazio (1945), made during a tropical cruise in the U.S.S. *Franklin*, that an effective temperature level of 78° F. is 'the approximate perspiration threshold for men in the resting state'.



Provided the effective temperature range was within the limits shown below, over 80 % of the votes recorded indicated that the voters were reasonably comfortable:

European men	73–79° F. E.T.
European women	72–78° F. E.T.
Asian men	71–81° F. E.T.
Asian women	76–80° F. E.T.

The lower limit of this ‘comfort zone’\* is less reliable than the upper limit, as it depends on smaller numbers of opinions. The zone is narrowest for the Asian women who were probably the least active group and exposed to the most uniform conditions, and greatest for the Asian men who recorded their votes under the least uniform conditions. Thus we may conclude that between effective temperatures of

Table 3. *Acceptable levels of warmth for groups of European (E.) and Asian (A.) men and women in Singapore*

		Dry-bulb temp. (° F.)		Wet-bulb temp. (° F.)		Effective temp. (° F.)	
		Men	Women	Men	Women	Men	Women
Upper limit of comfort zone:							
Over 80 % of voters were reasonably comfortable when the temperature was below	E.	84	82	79	76	79	78
	A.	85	85	80	78	81	80
Lower limit of comfort zone:							
Over 80 % of voters were reasonably comfortable when the temperature was above	E.	76	76	74	75	73	72
	A.	76	79	73	75	71	76
Less than 20 % of voters were ‘wet’ or ‘clammy’ below	E.	81	80	76	76	76	76
	A.	82	83	76	77	77	79
Less than 20 % of voters were wet with perspiration when the temperature was below	E.	87	83	80	78	80	80
	A.	86	89	80	80	80	82

76 and 78° F. the great majority of these lightly clad acclimatized men and women in Singapore felt neither too warm nor too cool and did not sweat perceptibly when they were engaged indoors in sedentary occupations.

*Comfortable levels of warmth for individuals*

The distribution of votes recorded at different levels of warmth by the individual subjects in each group was examined to ensure that the opinion of the group at any one level was not biased unfairly by the views of a single individual who might have chosen to record the majority of his or her votes under very much the same temperature conditions, or by predominant numbers of votes by cold-sensitive or warmth-sensitive people at either limit of the zone covered. The distributions of reasonably comfortable and total votes at various levels of effective temperature are shown in Table 4 for European men and women and in Table 5 for Asian men

\* In a previous study (Ellis, 1952) ‘comfort zone’ was used to refer collectively to the comfortably warm, comfortable and comfortably cool votes, described here as ‘reasonably comfortable’ votes. ‘Comfort zone’ is used here, more correctly, to mean the reasonably comfortable zone of warmth.



and women. There is little suggestion in Table 4 that individual bias seriously influenced the group opinion of the Europeans within the effective temperature zone of 73–81° F. to which the main conclusions of this paper refer, but in Table 5 it is clear that the opinion of the group of Asian men that reasonable comfort was

Table 4. Reasonably comfortable/total votes, for individuals at various ranges of effective temperature (° F.)

Subject	73–	74–	75–	76–	77–	78–	79–	80–	81–
European men									
1	4/6	9/10	13/13	16/17	17/19	18/19	9/27	2/13	0/1
2	4/4	2/2	12/13	11/11	18/18	17/25	6/13	1/8	1/4
3	2/3	11/13	9/10	8/8	18/19	25/29	6/13	4/8	1/4
4	1/1	—	8/8	9/9	27/28	22/26	10/18	2/15	1/3
5	3/3	7/8	13/14	15/17	19/21	9/14	3/7	3/9	0/3
6	6/6	5/5	8/9	10/10	9/10	12/12	13/13	20/24	12/13
7	—	2/2	2/2	10/10	16/16	19/19	23/31	13/19	1/7
8	6/6	7/7	11/11	18/18	28/28	33/33	26/27	30/37	14/25
9	—	—	4/4	6/7	16/16	18/22	14/21	9/16	4/12
10	—	1/1	4/4	14/14	29/29	17/18	22/25	4/8	3/5
11	2/2	4/4	6/6	18/18	36/36	27/27	23/23	11/15	5/7
12	—	2/2	—	2/2	12/12	15/16	25/25	26/26	9/10
13	4/4	9/9	8/8	9/9	13/13	25/25	8/8	5/5	6/9
14	1/1	5/5	10/10	11/11	21/21	19/21	9/14	2/8	2/3
15	0/1	—	1/1	4/4	5/5	10/11	10/11	21/23	16/18
16	—	0/1	2/2	2/2	8/8	17/17	18/18	15/17	6/7
17	6/6	9/9	15/15	21/23	32/33	23/23	39/40	37/37	20/21
18	—	2/2	4/6	4/4	10/11	14/14	13/14	5/8	3/5
19	0/1	5/5	6/6	7/7	13/13	7/10	7/14	1/9	0/4
20	1/2	1/1	1/1	1/1	2/2	5/6	2/2	4/5	20/24
21	1/1	1/1	—	—	3/3	2/4	4/5	7/10	6/8
Total R.C. votes	41	82	137	196	352	354	290	222	130
European women									
22	8/9	13/13	15/17	17/17	18/18	24/27	20/24	10/19	4/13
23	2/2	7/8	14/15	17/17	15/15	15/17	7/12	2/8	0/4
24	—	1/1	2/2	1/1	8/9	13/13	17/18	14/23	3/10
25	—	2/2	3/3	9/9	15/16	18/20	11/16	7/18	0/9
26	1/1	1/2	2/2	2/2	10/11	12/21	9/29	3/14	1/6
27	3/3	13/13	14/15	17/19	14/22	5/17	1/11	0/3	—
28	3/3	5/5	10/13	8/11	13/19	13/26	11/23	0/28	0/18
29	2/4	1/2	2/4	8/9	14/15	16/17	14/14	10/10	13/13
30	1/1	7/7	9/9	9/9	11/11	33/34	12/19	11/31	1/19
31	4/5	4/6	4/4	4/6	8/8	8/8	2/3	5/7	0/1
55	1/1	2/2	5/5	5/5	3/4	4/7	7/10	2/3	0/2
56	1/1	1/1	4/4	5/5	6/6	6/6	1/1	0/1	2/3
57	—	—	—	3/3	5/5	7/7	3/3	3/3	1/2
Total R.C. votes	26	57	84	105	140	174	115	67	25

enjoyed even when the effective temperature was 81° F. was largely due to the views of two subjects (34 and 36) who preferred a warmer climate than the others. If it had not been for these two men the opinion of the group would have coincided more closely with that of the European men.

Curves which show the percentages of reasonably comfortable votes of single individuals and of those reporting sweating at various levels of warmth were

constructed for fifty-seven subjects. Typical and atypical examples are illustrated in Fig. 3. Curves similar to the 'typical' curves were obtained for thirty subjects. The most frequent variation was that some subjects were very rarely uncomfortably warm at any time. The most common observation, however, when the warmth of the environment reached the level at which subjects began to feel too warm, was that the percentages of reasonably comfortable votes dropped steadily with each 1° F. rise in effective temperature, and reports of sweating increased in inverse proportion.

Table 5. '*Reasonably comfortable/total*' votes for individuals, at various ranges of effective temperature (° F.)

Subject	73-	74-	75-	76-	77-	78-	79-	80-	81-
Asian men									
32	4/6	4/10	8/11	14/15	23/23	29/29	29/31	23/29	7/13
33	3/3	7/8	4/6	11/11	16/16	18/20	12/15	7/13	2/5
34	1/1	1/1	4/4	6/6	11/11	5/5	14/14	21/21	13/13
35	—	—	3/3	1/1	15/15	15/15	14/15	26/30	9/20
36	1/1	4/4	5/6	7/7	2/2	12/12	11/11	10/10	14/14
37	1/1	1/1	3/3	10/11	9/10	18/18	15/16	14/15	3/4
38	—	5/5	4/4	6/6	11/11	16/16	15/15	21/21	8/13
39	1/1	—	5/5	8/13	8/14	6/16	7/18	2/2	—
40	3/3	—	2/2	9/9	13/15	19/20	14/16	4/5	2/5
41	2/2	6/6	10/10	19/19	22/22	10/11	2/2	1/1	—
42	1/2	3/4	7/7	9/9	18/19	19/19	9/9	—	—
43	1/1	6/6	8/10	4/5	12/20	7/10	2/5	2/2	—
44	5/5	5/6	4/4	12/12	8/8	6/7	2/2	0/1	—
45	—	—	1/1	5/5	13/13	21/21	9/9	—	—
Total R.C. votes	23	42	68	121	181	201	155	131	58
Asian Women									
46	—	1/1	1/1	5/5	11/11	37/39	37/39	29/36	20/32
47	—	1/1	1/1	7/7	14/14	25/25	41/41	34/34	22/27
48	—	—	—	7/7	11/11	32/33	35/36	15/29	8/29
49	—	—	—	3/3	6/7	23/24	21/24	18/28	5/15
50	0/1	4/4	7/8	4/4	23/24	12/13	17/19	13/20	4/6
51	—	—	3/3	1/1	10/10	22/22	13/13	29/30	12/12
52	4/4	4/4	2/3	6/6	11/11	12/14	12/16	8/13	2/4
53	0/2	4/5	8/11	8/8	17/17	19/19	9/10	3/3	—
54	0/1	0/3	3/5	6/6	17/19	17/18	6/6	2/2	—
Total R.C. votes	4	14	25	47	120	199	191	151	73

In Table 6 are shown the numbers of subjects for whom the upper and lower limits of the comfort zone lay at different levels of effective temperature. The limits of this zone, defined according to these arbitrary criteria, may vary widely between different individuals, and the difference between the distributions for Europeans and Asians is not marked. But, provided sufficient votes are recorded at each level of warmth, the response of the individual is usually remarkably consistent, even where the response is 'atypical'. For example, the curves for the European woman who did not record more than 80 % of votes in the comfort zone until the effective temperature was below 75° F. (subject 28) are shown in Fig. 3.

Both curves are consistent but show a shift to the left in comparison with all the other subjects. She was clearly a 'warm-sensitive' person. In contrast another European woman, subject 29, was 'cold-sensitive' and never felt uncomfortably warm in Singapore. She began to register increasing numbers of uncomfortably cool votes when the effective temperature dropped below 79° F. The Chinese man, subject 34, recorded more than 80 % reasonably comfortable votes even though the effective temperature was as high as 84° F. He obviously liked warm climates

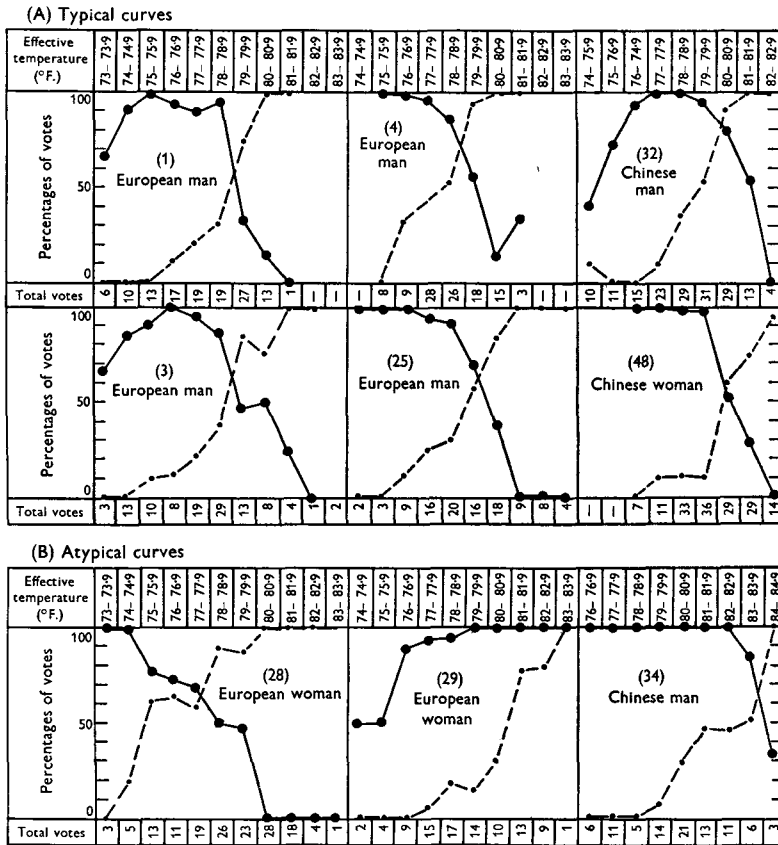


Fig. 3. Comfort and sweating of individuals at various levels of effective temperature. Continuous lines, 'comfortably cool', 'comfortable' and 'comfortably warm' votes; broken lines, wet or clammy skin.

more than the rest of the subjects shown in the frequency distribution, and the curves of many of the subjects included under column 11 of Table 6 as 'very rarely uncomfortably warm' were similar in character or showed an even greater shift to the right. Although nearly 18 % of these fifty-seven subjects were 'very rarely uncomfortably warm' when engaged in sedentary occupations indoors in Singapore, and nearly half of these were Europeans, 70 % (16/23 Asians and 24/34 Europeans) were 'very rarely uncomfortably cool'.

Thus the comfortable levels of warmth vary appreciably between individuals, and the larger the numbers which can be included in a survey of this kind the

better. However, intra-individual variability was unusual provided adequate numbers of votes were recorded over the particular temperature range.

Factors influencing group comfort

Level of activity. The contrast in Fig. 4 between the proportions of male students who were comfortable or sweating before and after the lectures indicates that, even when the difference in activity before recording their comfort votes was only that

Table 6. Variations in comfort responses of individuals

		No. of persons for whom the maximum effective temperature, at which more than 80% of votes were either 'comfortable', 'comfortably warm' or 'comfortably cool', was										Very rarely	Total no.
		84	83	82	81	80	79	78	77	76	75	uncomfortably	of
												warm	voters
European	Men	-	-	4	2	3	6	4	-	-	-	2	21
	Women	-	-	-	1	3	3	1	2	-	1	2	13
Asian	Men	1	-	1	4	2	1	-	1	1	-	3	14
	Women	-	-	1	1	3	1	-	-	-	-	3	9
All subjects		1	-	6	8	11	11	5	3	1	1	10	57

		No. of persons for whom the minimum effective temperature, at which more than 80% of votes were either 'comfortable', 'comfortably warm' or 'comfortably cool', was										Very rarely	Total no.
		79	78	77	76	75	74	73	72	71	70	uncomfortably	of
												cool	voters
European	Men	-	-	-	1	1	3	1	1	-	-	14	21
	Women	-	-	-	1	-	-	-	2	-	-	10	13
Asian	Men	-	-	-	2	1	-	-	-	-	-	11	14
	Women	-	-	-	3	-	1	-	-	-	-	5	9
All subjects		-	-	-	7	2	4	1	3	-	-	40	57

		No. of persons for whom the maximum effective temperature, at which less than 20% of votes reported sweating or clamminess of the skin, was										Sweating	Total no.
		82	81	80	79	78	77	76	75	74	73	never	of
												reported	voters
European	Men	-	-	1	-	4	8	6	2	-	-	-	21
	Women	-	-	1	1	3	2	4	1	1	-	-	13
Asian	Men	-	-	2	2	4	3	1	2	-	-	-	14
	Women	-	-	4	2	1	1	-	-	-	-	1	9
All subjects		-	-	8	5	12	14	11	5	1	-	1	57

between coming from the last class and sitting at rest for about an hour, the 'rest' in the lecture theatre reduced the proportions of voters who were sweating and increased the numbers who were comfortable for effective temperatures below 81°F.

Air movement. The beneficial effect of air movement when the air temperature exceeded 83° F. is illustrated in Fig. 5 by the increase with increasing air movement

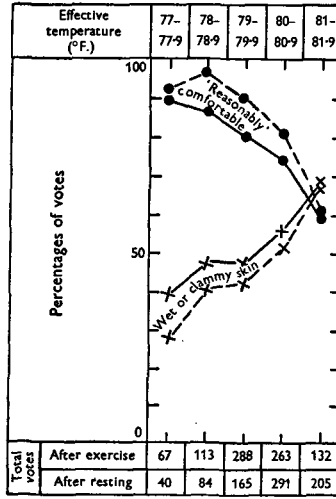


Fig. 4. Variations in comfort for a group of Asian male students, after light exercise and after resting for 1 hr., at various levels of effective temperature. Continuous lines, after light exercise; broken lines, after one hour resting.

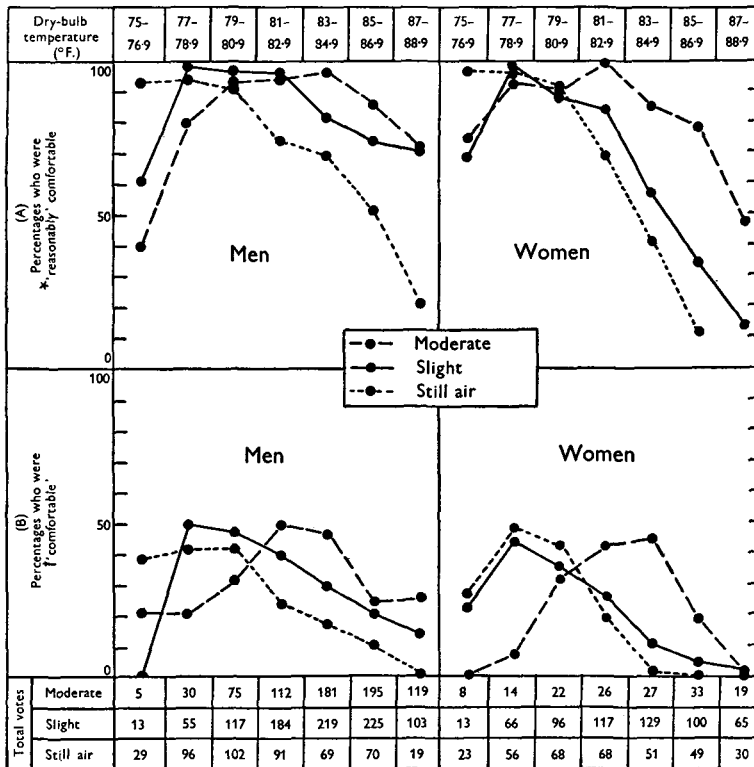


Fig. 5. Variations in comfort of Europeans due to differences in air movement at various levels of dry-bulb temperature.

\* 'Reasonably' comfortable = 'comfortably cool', 'comfortable' and 'comfortably warm' votes.

† 'Comfortable' = 'comfortable' votes only.

in the proportions of European men and women who were 'reasonably comfortable' or 'comfortable' at similar levels of air temperature. The zone within which increasing the air movement is likely to be of value is limited. When the air temperature was below 83° F. for the men and 81° F. for the women moderate air movement became more uncomfortable than slight air movement, whereas at higher levels of air temperature it was more comfortable. Below 77° F. still air was more comfortable than either slight or moderate air movement for both men and women.

*Race, sex and age.* The proportions of reasonably comfortable votes at different levels of effective temperature were compared graphically for European men and Asian men, European women and Asian women, European men and European women, Asian men and Asian women, European men over the age of 30 and under the age of 30, and for the Chinese and non-Chinese men students.

The European women preferred rather cooler conditions than the others, for they consistently recorded smaller proportions of reasonably comfortable votes and were more aware of wetness or clamminess of the skin under similar temperature conditions than either the European or Asian men or the Asian women. However, there were only thirteen European women subjects and even fewer Asians; the European women were on the average 9 years older than the Asian women, and rather older than the European men; the Asian women consisted largely of office workers who may have recorded their votes under more sedentary conditions than the European women. Thus it is not possible to say whether the preference of this group of European women for rather cooler conditions was due to differences in race or to differences in the sexes, ages or activities of the various groups. The group of men who were over 30 years of age preferred rather cooler conditions than the group under 30 years of age, particularly at the higher levels of warmth. The vote distribution for the Chinese male students was very similar to that for the European men, and indicated that as a group they were less tolerant of warm conditions than the non-Chinese Asian students.

The main conclusion to be derived from these comparisons is that in Singapore the comfortable levels of warmth for groups of acclimatized European men and women and Asian men and women residents are very similar, and are not markedly affected by differences in race, age or sex; although in this investigation the rather older group of European women who had been resident in the colony for less than 2 years preferred cooler conditions than the other groups.

#### DISCUSSION

The findings described apply to hot humid climatic conditions such as are encountered near to sea-level in the tropics where the air temperature ranges approximately between 70 and 90° F., and the relative humidity between 60 and 97%. Comfort votes were recorded only by persons who had lived in a tropical climate for more than 6 months. The comfortable levels of warmth might be different for newcomers from more temperate zones. All these subjects recorded their comfort votes under ordinary domestic or working conditions, not under controlled conditions in the laboratory. Apart from the general instructions that they should not

engage in heavy work beforehand and should be wearing light tropical clothing when recording their comfort votes, no further attempt was made to standardize the conditions of work and clothing. We have seen how at constant levels of warmth the metabolic effect of light activity before a lecture reduced the proportions of students who were reasonably comfortable in comparison with the proportions who were reasonably comfortable when the lecture was over and they had been at rest for about an hour. Houghten, Giesecke, Tasker & Gutberlet (1937) found that, in order to attain a similar degree of comfort, men wearing coats over light indoor clothing required effective temperatures 2–3° F. lower than men who were not wearing coats. The influence of air movement on comfort has been discussed. Variations in activity, clothing and air movement probably explain why only 56 % or less of those who voted were 'comfortable' at any one level of effective temperature in contrast with the results of the carefully controlled laboratory

Table 7. *Comfortable and optimum effective temperatures (° F.) for naval ratings who had served in a warship for six and twelve months in a warm climate, and for European and Asian residents in Singapore*

Distribution of votes	Men in warship (6/12 in a warm climate)	Men in warship (12/12 in a warm climate)	British residents (6/12–26/12 in a warm climate)		Asian residents	
			Men	Women	Men	Women
Less than 20 % reported sweating below	79	79	80	80	80	82
More than 80 % were reasonably comfortable below	80	79	79	78	81	80
Equal number of 'cool' and 'warm' votes were recorded at	74.5	74	76	74.5	75.5	77
Total votes available	1829	3382	2293	1257	1203	1044

experiments of the American Society of Heating and Ventilating Engineers (1950), in some of which more than 90 % of subjects were comfortable at certain effective temperature levels.

The relationships between effective temperature and the numbers of reasonably comfortable votes for two groups of naval ratings in a warship who were the subjects of two investigations reported previously (Ellis, 1952) and for these European men in Singapore are shown in Fig. 6. The desirable and upper acceptable levels of effective temperature are shown in Table 7.

Although the upper acceptable levels of warmth were similar for the men in the warship and for those in Singapore, Fig. 6 suggests that between effective temperatures of 80 and 85° F. the Singapore men were more tolerant of the higher levels of warmth than either group in the warship. In addition, when the effective temperature on the mess-decks was above 80° F. over 80 % of the ratings were stripped to the waist, and more than 50 % were stripped provided the effective



temperature was above 75° F. If they had all been wearing shirts like the Singapore men, the proportions of reasonably comfortable votes recorded by the ratings at each level of warmth would have been even lower, and the upper acceptable levels of warmth would probably have been similar to, or lower than, those for the Singapore men. The vote distribution also suggests that the Singapore men were more sensitive to chilling than either group of ratings when the effective temperature was below 75° F., which adds further support for the view that they were more acclimatized to life in a warm climate.

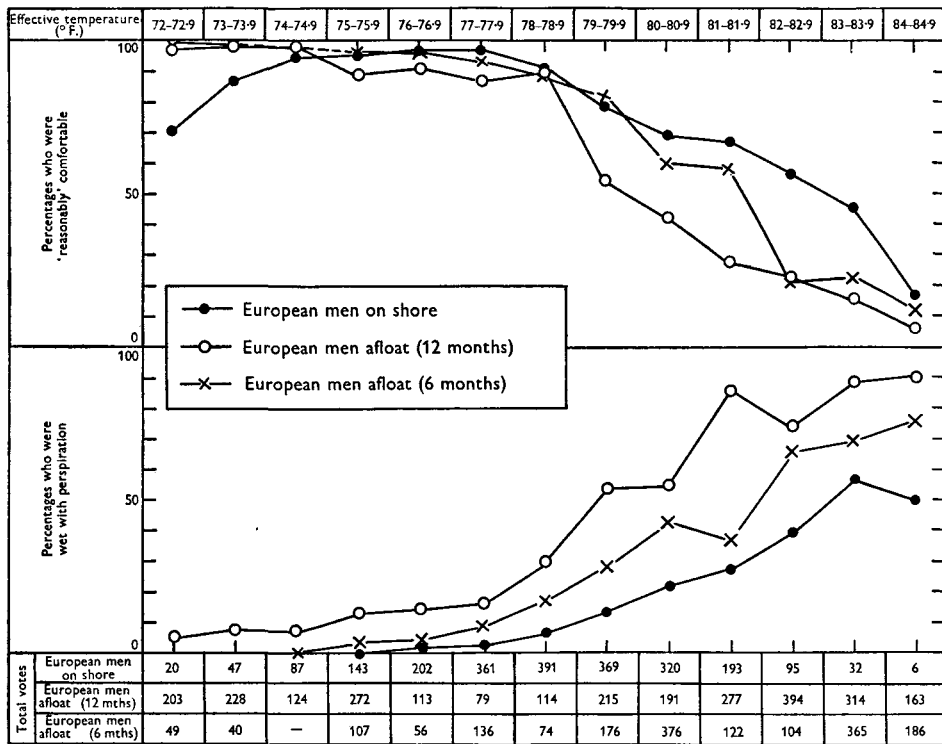


Fig. 6. Variations in comfort and sweating of European men living on shore and afloat at different levels of effective temperature.

It was suggested after these experiments in the warship that the upper level of warmth which should be accepted by those who design the ventilating systems of ships which are to operate in tropical waters should be an effective temperature of 78° F. This accords with the wartime standards accepted by the United States Navy for the tropics rather than 80° F., the level recommended provisionally to the Admiralty by the Royal Naval Personnel Research Committee in 1944 (Bedford, 1952). The present investigation supports the adoption of a similar standard for offices and dwellings in Singapore when this can be achieved. Furthermore, when allowance is made for the predominating influence of the votes of the two warmth-tolerant subjects which placed the upper limit of the comfort zone for Chinese men at 81° F. (Table 3), adjustment of this upper acceptable level for groups of different races appears to be unnecessary in Singapore.

Many European women who are temporary visitors to the tropics are less tolerant of tropical warmth than European men. It is debatable whether they do feel warmer than others when exposed to similar climatic conditions or whether some of them are unduly sensitive to minor irritations, of which the warm climate is only one, because they lead an incompletely filled existence or have failed to become adjusted to the domestic or social circumstances of their tropical environment. The results of this investigation suggest that the relative intolerance of this group of European women was because their perceptual threshold for unduly warm conditions was lower, and they did feel warmer and sweated more than the men under similar climatic conditions. However, Drysdale (1950) found women to be more heat-tolerant than men, and Yaglou & Messer (1941) found that scantily clad men and women laboratory workers at rest in an air-conditioned room both selected an effective temperature of 74–75° F. as the most comfortable level of warmth. It is probable that if differences in clothing, activity, age and acclimatization are taken into consideration the comfortable levels of warmth for males and females are very similar.

The comfortable levels of warmth for Singapore may be compared with similar standards for other parts of the world where the climate is warm. Rao (1952) recently came to the conclusion that in Calcutta the probable 'comfort ranges' all the year round are between 74 and 83° F. dry-bulb temperature and 68 and 76·5° F. effective temperature, and that the 'optimum' was 78·5° F. dry-bulb and 72·5° F. effective temperature. The seasonal variations in Calcutta are, however, more considerable than in Singapore. During 1951 the mean monthly air temperatures just before midday (11.53 hr. L.T.) differed by nearly 20° F. (75·8–95·6° F.), whereas in Singapore shortly after midday (12.30 hr. L.T.) the monthly difference was less than 5° F. (82·2–86·9° F.). The 'summer comfort zone' for Calcutta is probably similar to the 'annual comfort zone' for Singapore. In Iran an indoor effective temperature of 77·5° F. (D.B. 85° F.) was the upper limit for the 'comfort cooling' of the buildings of the Anglo-Iranian Oil Company during the hot weather (Grocott, 1948). During the summer at Sydney, Drysdale (1950) found that, for conditions of moderate humidity, a dry-bulb temperature of 88° F. was the critical level for the onset of discomfort for lightly clothed persons seated at rest performing light tasks, and that 86° F. should not be exceeded 'if conditions are humid and air movement is slight', but he emphasized that these were threshold conditions and that 84° F. was the desirable upper limit for calm humid conditions. Whilst the results reported here do not support his preference for dry-bulb temperature in place of effective temperature, perhaps because the factors of air movement and humidity are prominent in the Singapore environment, Table 3 indicates that they accord closely with his upper desirable level of dry-bulb temperature. The American Society of Heating and Ventilating Engineers' Committee on Sensations of Comfort (1942) recommend an indoor effective temperature of 73° F. for persons wearing normal indoor clothes during the summer in the southern States of North America.

It is consistent to record that the majority of lightly clad acclimatized European men and women engaged in sedentary occupations in Singapore—latitude 1° N.—

are comfortable when the effective temperature level is between 76 and 77° F., and more than 80 % are reasonably comfortable provided the effective temperature lies between 73 and 78° F. The levels of warmth preferred by Asian men and women residents may be rather higher; but if they are, and this has not been shown convincingly here, the differences are not great. These standards probably apply all the year round.

#### SUMMARY

The majority of sedentary lightly clad acclimatized European men and women in Singapore are reasonably comfortable in relation to their indoor thermal environment provided the effective temperature does not exceed 78° F. or fall below 73° F.

European women, who were, however, older as a group than the other subjects, preferred rather cooler conditions than European men or Asian men and women.

There were considerable variations between individuals in their comfort tolerance for various levels of warmth, but the average opinion of one individual was usually consistent provided sufficient votes were collected to provide an adequate sample at each level of warmth.

When the dry-bulb temperature was above 83° F., increasing the average air movement from a still to a more turbulent condition added to the comfort of the majority of European men and women. When the temperature was below 83° F. for men and 81° F. for women, moderately good air movement was rather less comfortable than slight air movement; whereas below 77° F. still air was more comfortable than slight or moderate air movement. Increasing the air movement within a compartment can thus be used for combating thermal discomfort only within a limited range of warmth, but within that range it is extremely useful.

Two groups of naval ratings who had been living in a warship in a tropical climate were reasonably comfortable at similar levels of warmth to the men in Singapore, but they were less tolerant of levels of warmth above the comfort zone.

I am deeply indebted to the numerous naval and civilian colleagues and friends who co-operated so willingly and made this investigation possible, to Dr T. Bedford and Miss H. M. Ferres for valuable comments, to the Director of the Regional Meteorological Centre, Calcutta, and the Director of the Malayan Meteorological Service, Singapore, for information on air temperatures, and to Mr Cheng Swee Guan for tabulating the comfort votes and preparing the illustrations.

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(MS. received for publication 8. I. 53.)