THE EFFECT OF RADIATION FROM THE SURROUNDINGS ON SUBJECTIVE IMPRESSIONS OF FRESHNESS

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(With 2 Figures in the Text)

I. INTRODUCTION

Many workers have studied the effects of the environment on subjective sensations of warmth, but few have devoted attention to its influence on subjective impressions of freshness. Warmth and freshness are mutually related in that a warm room is often stuffy while a cool room seems fresh, yet, of two equally warm rooms, one may appear to be fresh while the other is stuffy. The environmental factors which are associated with freshness have been reviewed by Bedford & Warner (1939), who investigated the effects of the strength and variability of air currents and of dry kata-thermometer cooling power and relative humidity on their own subjective impressions of freshness.

These workers recalled that the Commissioners of the General Board of Health advocated in 1857 that for comfort the temperature of the walls of a room should be at least as high as the general temperature of the room, and included cold walls or floors amongst the conditions which make for discomfort. Bedford & Warner said that 'although we have no statistical evidence to offer on this point, we are convinced that the Commissioners of 1857 were right. In the course of our field investigations, we have on a number of occasions experienced feelings of stuffiness at comfortable equivalent temperatures, when we have been unable to find any satisfactory explanation other than that the mean radiant temperature was 6° F. or more lower than the air temperature.' Bedford & Warner included in their list of the requirements for a pleasant and invigorating environment that the temperature of the walls and other solid surroundings should not be appreciably lower than that of the air, and should rather be higher.

It was because of the need for experimental evidence on this point that it was decided to study the subjective impressions of freshness of a large group of persons in relation to environmental conditions, paying particular attention to differences between mean radiant temperature and dry-bulb air temperature. The results of this study are described below.

II. EXPERIMENTS

The tests were carried out in the Heating Laboratory of the Building Research Station, Garston. The experimental room is about $12 \times 18 \times 9$ ft., with a volume of approximately 2000 cu.ft. The temperature of the walls, ceiling and floor can be separately controlled, and in all our experiments the ceiling and floor were maintained at the same temperature as that of the walls in order that radiation from the surroundings should be uniform. Although the temperature of the room air was under control it was not practicable to control the humidity. Of the staff of the Building Research Station, 106 men and 39 women volunteered to act as subjects. Conditions in the experimental room were arranged so that in some experiments the mean radiant temperature was below air temperature, while in others the mean radiant temperature and air temperature were equal, and in yet others the mean radiant temperature was higher than the air temperature. These conditions will be referred to as the cold-wall, neutral-wall and warm-wall environments respectively. Each of these three conditions was investigated at equivalent temperatures of approximately 60, 65 and 70° F., so that there were nine different environmental conditions. It was not possible for all the subjects to attend on nine occasions, but most of them could attend on three. It was therefore decided to separate the subjects into three groups—*A*, *B* and *C*—of approximately equal numbers to be tested at 60, 65 and 70° F. equivalent temperature respectively. Thus, a subject in Group A was tested in cold-, neutral- and warm-wall environments, each of the three environments being at an equivalent temperature of 60° F. The tests were carried out in 1948 from January to June in the following order: neutral walls in January and February, cold walls in March and April, and warm walls in May and June. The subjects attended on their second and third visits in the same weight of clothing as on their first visit.

The environmental conditions are summarized in Table 1. The differences between the mean radiant temperature and the air temperature were about

5 and 3° F. for cold- and warm-wall environments respectively. With the present equipment in the test room it was not possible to obtain larger differences between the mean radiant temperature and the air temperature, and the differences were obtained by the use of auxiliary air heating in the cold-wall environment, and of auxiliary wall heating in the warm-wall environment. Air movement was low throughout the tests. The measurements made during the tests are described below.

Environmental measurements

The environmental measurements made inside the experimental room included dry- and wet-bulb air temperatures, mean radiant temperature, air movement, rate of air change and globe thermometer temperature. Generally, the air temperature was measured by means of mercury-in-glass thermometers, and radiation errors were minimized by fitting cylindrical shields of aluminium foil to the thermometers. The atmospheric humidity was ascertained from the readings of a whirling hydrometer. The mean radiant temperature was obtained from direct measurement of radiation made with a Moll thermopile; for the measurements of air movement, silvered kata-thermometers were used, and the rate of ventilation was measured regularly with a katharometer. Owing to fluctuating mains voltages and to power cuts, it was not possible to use the eupatheoscope, and thus to obtain direct measurements of the equivalent temperature. Instead, equivalent temperatures were calculated from the equation (Bedford, 1936):

Equivalent temperature

$$= 0{\cdot}522\, t_a + 0{\cdot}478\, t_w - 0{\cdot}01474 \sqrt{v}\,(100 - t_a),$$

where t_a is the air temperature in ° F., t_w is the mean radiant temperature in ° F., and v is the rate of air movement in ft./min. The effective temperatures quoted are those for clothed resting subjects.

As a routine, measurements of the temperature, humidity and rate of air movement were made at a height of 4–4½ ft. from the floor. Other measurements of air temperature and air movement were made at a level of 6 in. from the floor, except in the experiments on cold walls when, for reasons which will be explained later, the measurements were made at a height of 12 in. from the floor.

In rooms heated mainly by convection it has often been found that there are considerable differences between the temperatures of the air at head and foot levels. Such vertical temperature gradients occurred in the test room when the walls were cold and the air warm, and these had to be eliminated before the tests were started, for it has been stated that such gradients tend to evoke feelings of stuffiness. These gradients could have been reduced by more thorough mixing of the room air, but this procedure would have produced undesirably high rates of air movement, and so another method was used. Low, slotted, wooden platforms were made and placed beneath the tables at which the subjects sat, and under each platform a sheet of aluminium foil was fitted. A wire grid was suspended underneath the aluminium foil and supplied with an electric current sufficient to warm the platform surface and the air above it to a temperature which differed very little from the temperature of the air at head level. The temperatures of the platform surfaces were measured with the thermopile, and the air temperatures at levels of 1 and 12 in. above the platform were measured with a thermocouple. These measurements were made as a routine in the cold-wall environments. In order to obtain a sufficient difference between the mean radiant temperature and the air temperature it was found necessary to use auxiliary air heating. A small

Table 1. *The mean values of environmental factors together with mean warmth and freshness votes*

Type of environment ...		Cold walls			Neutral walls			Warm walls		
Subject group ...		*A*	*B*	*C*	*A*	*B*	*C*	*A*	*B*	*C*
No. of observations		43	40	41	46	42	46	43	40	39
Dry-bulb air temperature, ° F. (t_a)		62·8	68·3	74·0	60·6	65·9	70·8	61·0	66·2	69·6
Wet-bulb air temperature, ° F.		52·7	56·4	59·6	53·0	57·0	58·3	50·1	52·8	54·4
Mean radiant temperature, ° F. (t_w)		59·2	63·9	67·6	61·0	66·0	70·9	63·9	69·0	73·2
$(t_w - t_a)$, ° F.		−3·6	−4·4	−6·4	+0·4	+0·1	+0·1	+2·9	+2·8	+3·6
Air velocity, ft./min.		14	13	12	10	13	11	13	14	13
Vapour pressure, mm. Hg		7·5	8·5	9·1	8·3	9·5	9·1	6·3	6·4	6·5
Relative humidity, %		52	48	42	60	58	47	46	39	35
Effective temperature, ° F.		60·2	64·6	68·6	58·9	63·3	66·6	58·5	62·3	64·7
Equivalent temperature, ° F.		59·0	64·5	69·7	59·0	64·2	69·3	60·3	65·7	69·7
Equivalent warmth, ° F.		57·8	62·7	67·1	57·9	62·5	67·1	58·5	63·5	66·5
Sensations of warmth	After 30 min. exposure	−0·5	+0·1	+0·6	−0·9	−0·7	+0·3	−0·9	−0·4	−0·2
(arbitrary units)	After 90 min. exposure	−1·1	−0·2	+0·2	−1·1	−0·5	0	−1·0	−0·6	0
Impressions of freshness	After 30 min. exposure	4·0	3·2	2·9	4·3	3·9	2·9	4·7	4·4	4·3
(arbitrary units)	After 90 min. exposure	4·2	3·4	3·1	4·3	3·9	3·2	4·8	4·4	4·2

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electrical convector was placed on the floor at each of the four corners of the room, and further air heating was obtained when necessary from a 3 kW. convector. These heaters were screened by shields made from perforated aluminium foil, so as to reduce radiation to a minimum.

In the warm-wall environment vertical temperature gradients did not occur. The entry of cold air increased the rate of air movement, but this was reduced by the use of a cloth screen between the air inlets and the subjects. Sufficiently large differences between the mean radiant temperature and air temperature could not be obtained without auxiliary wall heating. For this purpose, electrically heated panels were used. Each panel was 3 × 2 ft. in size, with a maximum load of 500 W. Two panels were fixed to each wall at about 3 ft. from the floor, so that eight panels were available for extra wall heating. In practice, the panels on three walls were used because, in order to avoid floor draughts, it was necessary for the subjects to sit nearer one long wall instead of in the centre of the room. The surface temperatures of the panels were not allowed to exceed 100° F.

The rate of ventilation varied from 2 to 3·5 air changes per hr. The higher rate was usually found necessary in the warm-wall environment, in order to maintain sufficient difference between the mean radiant temperature and air temperature. Even if there were six people in the room with only two air changes per hr., the supply of fresh air per person was 660 cu.ft./hr., and with 3·5 air changes it was 1200 cu.ft. These rates of ventilation were sufficient to prevent body odours from affecting impressions of freshness.

Sensations of warmth and impressions of freshness

The subjects were asked to assess their sensations of warmth and impressions of freshness, and their responses were recorded on the following scales (Bedford, 1936; Bedford & Warner, 1939):

Warmth		Freshness	
Much too warm	+3	Very stagnant	0
Too warm	+2	Very stagnant to stagnant	1
Comfortably warm	+1	Stagnant	2
Comfortable	0	Stagnant to medium	3
Comfortably cool	−1	Medium	4
Too cool	−2	Medium to fresh	5
Much too cool	−3	Fresh	6
		Fresh to very fresh	7
		Very fresh	8

The qualitative scale of warmth sensations is that used by Bedford, but the numerical marks assigned have been changed. Bedford used a scale ranging from 'much too warm' = 1 to 'much too cool' = 7.

The subjects were questioned concerning their freshness votes in order to ascertain the reasons underlying the reactions reported. In the warm-wall environment each was asked to state whether that environment was more or less pleasant than the cold-wall environment to which he had been exposed in an earlier experiment, or whether there was no noticeable difference between the two environments.

The initial subjective reactions were first noted when the subjects had been in the test room for at least half an hour, and the final reactions were noted an hour later.

During the test period the subjects were occupied in much the same way as in their own offices. The only activity definitely prohibited was smoking. The subjects sat near tables during the tests. Sometimes there were four subjects in the room, and there were never less than two.

III. RESULTS

Table 1 gives the mean values of the principal environmental measurements made in each of the nine environments. It also shows the mean values, in arbitrary units, of warmth and freshness impressions on the first and second votes in each environment. Inspection of the table shows that the average differences between the mean radiant temperature and the air temperature were 3 and 5° F. for the warm-wall and the cold-wall environments respectively. In Fig. 1, the mean freshness votes after 30 and 90 min. exposure to the nine environments are plotted against mean equivalent temperature. The graphs show that an increase in equivalent temperature is associated with decreased freshness for all types of environment; that at a given equivalent temperature the warm-wall environment feels fresher than either of the other two environments; that the neutral-wall environment seems fresher than the cold-wall environment; that the difference between the freshness experienced in the warm-wall environment and that felt in the other two environments was greatest at the highest equivalent temperature; and that the difference between the warm-wall environment and the neutral wall environment is greater than the difference between the neutral- and the cold-wall environments.

It should be noted that the differences between the mean radiant temperature and the air temperature in the warm-wall environment are, on the average, less than in the cold-wall environment. Fig. 2 shows the mean freshness votes plotted against the average differences between the mean radiant temperature and the air temperature. It indicates that an environment with warm walls has a relatively greater effect on impressions of freshness than one with cold walls.

The data upon which Figs. 1 and 2 are based, however, do not include all the physical factors which could have affected impressions of freshness. Atmospheric humidity was not controlled, and varied considerably during the experiments. The rate of air movement was practically constant at 13 ft./min. in all the tests, and therefore does not appear in this investigation as one of the factors affecting impressions of freshness. Air movement is an important factor affecting freshness, but it was not studied in the present experiment, in order to limit the number of variables being examined, and also because its relation to freshness has previously been studied (Bedford & Warner, 1939).

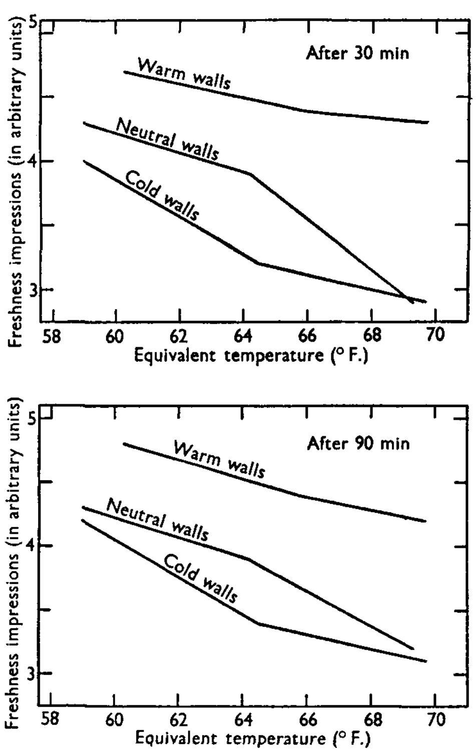

Fig. 1. Impressions of freshness (in units on the arbitrary scale) of environments with warm, neutral and cold walls, plotted against equivalent temperature, ° F., after 30 and 90 min. exposure.

The influence of body odour on the impressions of freshness was also eliminated by adequate ventilation. Attention was therefore concentrated on determining quantitatively the effects of sensations of warmth, atmospheric humidity and the difference between mean radiant temperature and air temperature on impressions of freshness.

Table 2 shows zero-order correlation coefficients of freshness votes, after 30 and 90 min. exposure, with general warmth sensations and environmental factors. For either period of exposure, the highest correlation is between dry-bulb air temperature and impressions of freshness, which means, since the correlation coefficient is negative, that the environment seems less fresh at the higher air temperatures. The correlation coefficients between impressions of freshness and general warmth sensations, vapour pressure, and the difference between mean radiant temperature and air temperature are all statistically significant. Decreased sensations of general warmth, lowered equivalent temperature or vapour pressure, and increased difference between mean radiant temperature and dry-bulb air temperature are all associated with increased impressions of freshness.

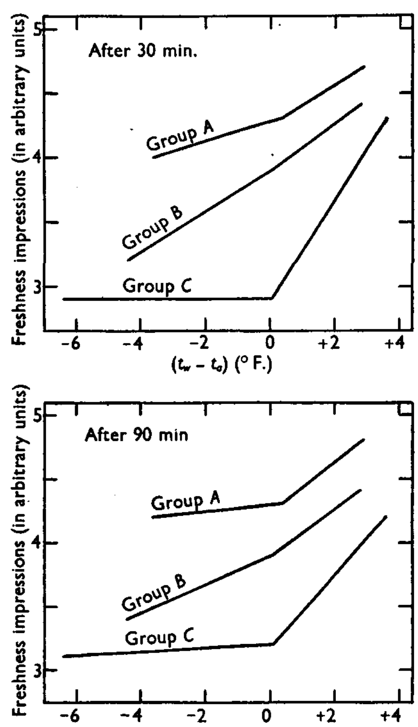

Fig. 2. Impressions of freshness (in units on the arbitrary scale) plotted against the difference between mean radiant temperature (t_w) and air temperature (t_a) for equivalent temperatures of approximately 60° F. (Group *A*), 65° F. (Group *B*) and 70° F. (Group *C*), after 30 and 90 min. exposure.

The zero-order association between impressions of freshness and relative humidity is statistically insignificant.

As the zero-order correlations of freshness with equivalent temperature show, a cool environment tends to feel fresh and an over-heated one stuffy. Yet even when the general level of warmth is satisfactory one may experience feelings of freshness or of stuffiness, and it is interesting to ascertain from our data how various thermal factors influence freshness impressions when the overall warmth of the environment is held constant.

Equivalent temperature is a good index of warmth over the range of conditions included in our study, and we have calculated partial correlation coefficients for freshness with different variables holding equivalent temperature constant. These coefficients are set out below:

Freshness impressions correlated with	Partial correlation coefficient (equivalent temperature constant)
Dry-bulb air temperature	$-0{\cdot}40 \pm 0{\cdot}043$
Vapour pressure	$-0{\cdot}39 \pm 0{\cdot}043$
Mean radiant temperature	$+0{\cdot}47 \pm 0{\cdot}040$

When the equivalent temperature is held constant an increase in the air temperature (which was accompanied by a compensatory change in one of the other variables, e.g. a lowering of the mean radiant temperature) reduced the apparent freshness of the environment. Similarly, an increase in the absolute humidity, as measured by the vapour pressure, reduced freshness. On the other hand, an increased mean radiant temperature, which meant a reduced air temperature, was associated with increased freshness. Although earlier work has shown that equivalent temperature is a good measure of warmth, its association with warmth sensations is not perfect. Furthermore, although atmospheric humidity has but a slight influence on sensations of warmth at the temperatures with which we are here concerned, equivalent temperature makes no allowance for it. Hence, in order to make certain whether the vapour pressure, general sensations of warmth, and the difference between mean radiant temperature and air temperature, are each independently associated with impressions of freshness, partial correlation coefficients have been calculated and are given in Table 3. The partial correlation coefficients are all statistically significant, showing that each of the three variables referred to above is independently associated with impressions of freshness.

Thus when one experiences the same feeling of general bodily warmth an increase in the absolute humidity reduces the feeling of freshness, while an increase in the excess of the mean radiant temperature over the air temperature increases it. The regression equations based on these partial correlation coefficients are given below:

Table 2. *Impressions of freshness correlated with sensations of warmth and environmental factors*

Impressions of freshness correlated with	Period of exposure: 30 min. Correlation coefficient	30 min. Standard error	90 min. Correlation coefficient	90 min. Standard error
Dry-bulb air temperature	$-0{\cdot}472$	$\pm 0{\cdot}040$	$-0{\cdot}461$	$\pm 0{\cdot}040$
Sensations of warmth	$-0{\cdot}444$	$\pm 0{\cdot}041$	$-0{\cdot}383$	$\pm 0{\cdot}044$
Vapour pressure	$-0{\cdot}437$	$\pm 0{\cdot}042$	$-0{\cdot}389$	$\pm 0{\cdot}044$
$(t_w - t_a)$	$+0{\cdot}388$	$\pm 0{\cdot}044$	$+0{\cdot}321$	$\pm 0{\cdot}046$
Equivalent temperature	$-0{\cdot}380$	$\pm 0{\cdot}044$	—	—
Mean radiant temperature	$-0{\cdot}175$	$\pm 0{\cdot}050$	$-0{\cdot}228$	$\pm 0{\cdot}049$
Relative humidity	$-0{\cdot}065$	$\pm 0{\cdot}051$	$+0{\cdot}027$	$\pm 0{\cdot}051$
No. of observations	380		380	

Table 3. *Partial correlation of impressions of freshness with sensations of warmth and environmental factors*

Impressions of freshness correlated with	Correlation coefficient	Standard error	Factors held constant
	After 30 min. exposure		
Vapour pressure	$-0{\cdot}282$	$\pm 0{\cdot}047$	Warmth sensations and $(t_w - t_a)$
$(t_w - t_a)$	$+0{\cdot}152$	$\pm 0{\cdot}050$	Warmth sensations and vapour pressure
Warmth sensations	$-0{\cdot}363$	$\pm 0{\cdot}045$	$(t_w - t_a)$ and vapour pressure
	After 90 min. exposure		
Vapour pressure	$-0{\cdot}241$	$\pm 0{\cdot}048$	Warmth sensations and $(t_w - t_a)$
$(t_w - t_a)$	$+0{\cdot}144$	$\pm 0{\cdot}050$	Warmth sensations and vapour pressure
Warmth sensations	$-0{\cdot}332$	$\pm 0{\cdot}046$	$(t_w - t_a)$ and vapour pressure

30 min.: freshness

$$= 5{\cdot}450 - 0{\cdot}383\ W - 0{\cdot}216 f + 0{\cdot}047\ (t_w - t_a), \quad \text{(i)}$$

90 min.: freshness

$$= 5{\cdot}329 - 0{\cdot}341\ W - 0{\cdot}183 f + 0{\cdot}044\ (t_w - t_a), \quad \text{(ii)}$$

where W = warmth vote, f = vapour pressure (mm. Hg) of the air, t_w = mean radiant temperature, ° F., t_a = dry-bulb air temperature, ° F. The regression coefficients in these equations indicate that with the same warmth sensation the effect of a change in the

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vapour pressure, or in the difference between mean radiant temperature and air temperature, on impressions of freshness is small.

In our experiments the air was calm, so that the mean air speed was not a variable worth taking into account. The magnitude of the effect of each of the other thermal variables (air temperature, mean radiant temperature and vapour pressure) on freshness impressions after 30 min. exposure is shown in the equation:

$$\text{Freshness} = 8{\cdot}66 - 0{\cdot}086\,t_a + 0{\cdot}037\,t_w - 0{\cdot}193f, \quad \text{(iii)}$$

where freshness is measured in the units on our arbitrary scale, t_a is the dry-bulb air temperature in ° F., t_w is the mean radiant temperature in ° F., f is the vapour pressure of the air in mm. Hg. The regression constants indicate that from the standpoint of freshness a rise of 5° F. in air temperature can be compensated by a rise of 12° F. in the mean radiant temperature or a reduction of the vapour pressure by 2·2 mm. Hg.

It has already been noted that on the whole a warm environment tends to feel less fresh than a cooler one, and it is therefore of interest to note that not only does an increase in the excess of the mean radiant temperature over the air temperature increase freshness, but that when all the other thermal variables are held constant an increase in the mean radiant temperature increases freshness. This increase in radiant heat makes one feel fresher, even though it also makes one feel warmer.

It is apparent from the previous paragraph that the weighting of the effects of the different thermal variables on impressions of freshness is not the same as their weighting with respect to warmth sensations. This point will be made more clear if the constants in equation (iii) are compared with Bedford's (1936) equation in which he expressed the warmth sensations of his subjects in terms of the individual factors of the thermal environment. That equation, in terms of the numerical values of warmth sensations used by us, is

$$W = 0{\cdot}0556t_a + 0{\cdot}0538t_w + 0{\cdot}0372f - 0{\cdot}00144\sqrt{V}\,(100 - t_a) - 7{\cdot}16, \quad \text{(iv)}$$

where W is the numerical value of the warmth sensation, and V is the rate of air movement in ft./min. In our observations the rate of air movement was practically constant at 13 ft./min., and substituting that value, equation (iv) as it can be applied to the conditions of our experiments is

$$W = 0{\cdot}0608t_a + 0{\cdot}0538t_w + 0{\cdot}0372f - 7{\cdot}68. \quad \text{(v)}$$

From this equation it appears that a rise of 5° F. in the dry-bulb temperature of the air is equivalent to a rise of 5·7° F. in the mean radiant temperature, or of 8·2 mm. Hg in the vapour pressure. We have already noted that with respect to freshness impressions a rise in the air temperature is equivalent to a fall in the mean radiant temperature. Whereas from the standpoint of freshness a rise of 5° F. in the air temperature can be compensated by a reduction of only 2·2 mm. in the vapour pressure, the compensatory reduction of vapour pressure needed from the standpoint of warmth sensations is 8·2 mm. Thus, although atmospheric humidity has but a very slight influence on warmth sensations at the temperatures which prevailed in our experiments, it has substantially more effect on impressions of freshness.

In equation (i) the numerical values of freshness impressions are expressed in terms of warmth sensations, vapour pressure, and the difference between mean radiant and air temperatures, while equation (iii) expresses freshness sensations in terms of the dry-bulb air temperature, mean radiant temperature and vapour pressure. It is, perhaps, of interest to use the modified form of Bedford's equation for warmth sensations, (v) above, to substitute for W in our equation (i). When this is done, equation (i) becomes

$$\text{Freshness} = 6{\cdot}86 - 0{\cdot}070t_a + 0{\cdot}026t_w - 0{\cdot}230f. \quad \text{(vi)}$$

This equation is in fairly good agreement with equation (iii) which was obtained entirely from our own data, and it indicates that our subjects' warmth requirements were very similar to those of Bedford's subjects.

That the zero-order correlations between relative humidity and freshness impressions were insignificant is due to the fairly close inverse relationship between air temperature and relative humidity ($r = -0{\cdot}469$). When air temperature is held constant, there are significant partial correlations between freshness impressions and relative humidity ($r = -0{\cdot}367$ and $r = -0{\cdot}241$ after 30 and 90 min. exposure respectively). The regression constants indicate that, to keep freshness impressions constant, a rise of 1° F. in the air temperature must be compensated by lowering the relative humidity by 5 %.

It is of some interest to know whether the influence of environmental factors on impressions of freshness varies with the period of exposure. The correlations between impressions of freshness and environmental variables after the two periods of exposure are compared in Table 2. In every instance, the association is closer at the end of 30 min. than after 90 min. The regression constants based on these correlations show that, after 90 min., a slightly greater change of the variable concerned is required to produce a given change in freshness impressions.

The data already presented show that the impressions of freshness are greatest in the warm-wall environment and Table 4 shows that, on the whole, 73% of the subjects considered the warm-wall environment more pleasant than the cold-wall environment. The higher the equivalent temperature, the greater was the percentage of subjects preferring the warm-wall environment. At equivalent temperatures of 60, 65 and 70° F., the proportions of subjects preferring the warm-wall environment were 54, 83 and 84 % respectively.

Table 4. *Warm-wall and cold-wall environments compared with respect to impressions of pleasantness, the replies of the subjects being expressed as percentages*

Equivalent temperature (° F.)	Warm walls more pleasant than cold walls (%)	Cold walls more pleasant than warm walls (%)	No difference between warm and cold walls (%)	Totals (%)
60	54	19	27	100
65	83	8	9	100
70	84	8	8	100
All temperatures	73	12	15	100

IV. DISCUSSION

The primary object of the experiment was to ascertain the effects of radiation from the surroundings on impressions of freshness. The relative effects of warmth sensations, atmospheric humidity, and the differences between the mean radiant temperature and the dry-bulb air temperature on impressions of freshness after exposures of 30 and 90 min., are shown in equations (i) and (ii) respectively. The effects of dry-bulb air temperature, mean radiant temperature, and atmospheric humidity on impressions of freshness after 30 min. exposure are given in equation (iii). The constants of these equations indicate that the effects of mean radiant temperature on impressions of freshness are not great, but our results are in accord with earlier statements that a cold-wall environment tends to be associated with impressions of stuffiness, and conversely, that a warm-wall environment tends to feel fresh.

We suggest that the impressions of stuffiness experienced in a cold-wall environment are usually not due solely to the difference between the mean radiant temperature and the air temperature. Cold-wall environments are commonly produced by convection heating, and this often causes the temperature of the air at head level to be substantially higher than that at floor level. With such vertical temperature gradients, overheating of the head is liable to produce sensations of stuffiness. In our experiments care was taken to eliminate such air temperature gradients so that such gradients introduced no complication.

It was not practicable to control the atmospheric humidity during our experiments, however, and there is reason to suppose that differences between the humidities which prevail in the different types of environment were largely accountable for the greater freshness experienced with warm walls. It is true that with the vapour pressure held constant an increase in the mean radiant temperature caused a small increase in freshness, but a decrease in the vapour pressure also increased freshness. In our warm-wall environments the vapour pressure was 2 or 3 mm. less than in the cold-wall environments (Table 1), and this difference in atmospheric humidity undoubtedly contributed to the fresher feeling of the warm-wall environment.

So far in this discussion we have considered atmospheric humidity in terms of vapour pressure. It has been remarked earlier that the insignificant zero-order correlation between relative humidity and freshness impressions was due to an inverse relationship between air temperature and relative humidity. The higher relative humidities were observed at the lower air temperatures. When air temperature was held constant there was a significant negative partial correlation between freshness impressions and relative humidity. From equation (iii) it can be calculated that when the mean radiant temperature is held constant and the air temperature is reduced from 61 to 60° F., the necessary compensatory rise of about 0·45 mm. Hg in the vapour pressure, if the same freshness value is to be maintained, represents a rise of 5 % in the relative humidity. If the air temperature and the mean radiant temperature are both reduced by 1° F. the equivalent change in relative humidity is about 4 %. In their earlier work Bedford & Warner (1939) found that, on the basis of freshness impressions, an increase of 1° F. in the room temperature was equivalent to raising the relative humidity by 8·5 %. From Bedford's (1936) data on warmth sensations (equation (iv), above) it can be calculated that to maintain equal warmth when the air temperature and mean radiant temperature are both reduced from 61 to 60° F. the relative humidity must be increased by 24 %.

From these earlier data it appeared that the humidity of the environment had a considerably greater effect on impressions of freshness than upon sensations of warmth, and the results of our experimental study give clear-cut support to this conclusion.

The rate of air movement in these experiments was not sufficiently high to evoke tactile sensations. Bedford (1948), referring to the observations of Vernon, Bedford & Warner (1926), stated that the rates of air movement encountered by these workers were not high enough to evoke sensations of touch and that impressions of freshness were almost certainly due to stimulation of the thermal receptors. On being questioned concerning the reasons for their assessments of freshness, some of our subjects mentioned sensations of warmth on the face in cold-wall environments and sensations of coolness on the face in the warm-wall environments, and all impressions of freshness were referred to the head. It would appear that impressions of freshness experienced by our subjects were due to stimulation of the thermal receptors of the head. The skin and subcutaneous tissues of the head are richly innervated and highly vascularized, and they are maintained normally at a higher temperature than any other exposed surface of the body, varying only slightly over a wide range of air temperatures. Thus the rate of heat loss from the head is liable to fluctuate more with variations in environmental temperature, air movement, and humidity than in other regions.

The thermal receptors of the head will be stimulated to a greater extent than those of other regions by changes in the environment. The importance of air movement is that it affects the rate of heat loss by both convection and evaporation and that it tends to be variable. It is possible that while sensations of general warmth appear to depend on the summated effects of the environment on the whole body, impressions of freshness are probably related to transient, and often quite small, fluctuations in the rate of heat loss from the head.

The temperature sense is not uniform over the head. The scalp is very insensitive to changes in temperature but the nose is a region which is very sensitive to thermal stimuli.

During respiration, the same physical factors, excepting radiation, which affect the rate of heat loss from the external skin surface, also influence the nasal mucous membranes. Lowering the air temperature and humidity increases the difference between the vapour pressure at the surfaces of the nasal membranes and the air, and also the difference between the temperature of the surfaces of the nasal membranes and the air; thus, the rate of intra-nasal cooling at each inspiration is increased. The resulting increased intra-nasal stimulation may be expected to produce impressions of freshness. Conversely, any environmental condition which tends to reduce intra-nasal cooling and increase intra-nasal vascular congestion, will tend also to produce impressions of stuffiness, and often actual obstruction to nasal breathing. An environment with a rather low air temperature, which otherwise might be termed fresh, may seem stuffy merely because the humidity of the inspired air is high.

In places where the air temperature at head level is considerably higher than at floor level, impressions of stuffiness are often experienced. Bedford & Warner (1939) found that their impressions of freshness were usually less in rooms where the air was at a lower temperature at floor level than at head level. They state that the stuffy impressions can be produced by any local chilling of the feet, whether due to temperature gradients or draughts. In some other experiments which we have carried out and during which severe local chilling of the feet was produced, we do not recollect any impressions of stuffiness (Munro & Chrenko, 1948). Furthermore, using our present data, we found that the partial correlation between freshness impressions and local sensations of warmth on the feet was insignificant when general body warmth sensation was held constant. In our opinion, therefore, the sensations of stuffiness which are associated with steep temperature gradients are not so much due to local chilling of the feet as to the tendency to reduced rate of heat loss from the head, and to intra-nasal congestion directly resulting from the high air temperature at head level. When a localized source of high-temperature radiation is used, the air temperature is usually sufficiently low at head level, provided no excessive radiation impinges on the head, to prevent the onset of impressions of stuffiness. It is to be expected that the impressions of freshness will be greater also with this localized type of heating than with the same mean radiant temperature produced uniformly from the surrounding surfaces, because variations in thermal stimulation of the face will occur with every movement of the head. However, if the source of radiant heat is near the head, for example, with low ceiling panels, local overheating of the head may evoke impressions of stuffiness.

It is of interest to compare the average freshness votes recorded in the three types of environment studied. The mean votes at each level of equivalent temperature are shown in Table 1. The average freshness votes in the cold-wall environments were generally rather lower than in the neutral-wall environments, and when the data for all three temperatures were combined the difference between the means for the two types of environment was just statistically significant. The average freshness vote in the warm-wall environments was significantly higher than that for either of the other two types of environment.

The data in Table 4 show clearly that the warm-wall environments, in addition to feeling fresher than the others, were also generally regarded by our subjects as being the most pleasant.

Bedford & Warner (1939) drew attention to the profound effect of air movement on freshness, and they found that at different seasons, an increase of 20 or 40 ft./min. in the air velocity was required to increase the freshness impression by one unit. Increasing the air velocity is often a simple, cheap and yet effective method of freshening an environment, yet, an environment made fresh by rapid air movement would not necessarily be pleasant. On the other hand, as our data show, relatively calm air need not produce a stuffy environment.

We conclude that when fluctuations in the rate of heat loss from the head increase, from whatever cause, the environment seems fresher, and conversely, when they are reduced, sensations of stuffiness are experienced. Stimulation is probably localized, at any rate to a large extent, in the face and the nasal mucosa. The face is exposed to the effects of convection, radiation and evaporation, whereas the nasal membranes are affected only by convection and evaporation, unless radiation has an effect reflexly through the skin. Thermal contrast effects may be thus invoked to explain the sensations of greater freshness in a warm-wall environment when other factors are held constant. Since the vapour pressure of the surfaces of the nasal membranes is higher than that of the skin, and since the membranes are more sensitive than the external skin, stimuli arising from evaporative cooling will be greater in this region than on the skin surface. This may be an explanation of the fact that changes in humidity which are insufficient to affect general warmth sensations affect impressions of freshness.

V. SUMMARY

The effects of radiation from the surroundings on the impressions of freshness of 106 men and 39 women members of the staff of the Building Research Station were investigated during the first 6 months of 1948. Subjects were exposed to three types of environment: (1) where the walls were cooler than the air, (2) where the walls and air were at the same temperature, and (3) where the walls were warmer than the air. The tests were carried out in calm air.

It was found that the difference between the mean radiant temperature and the air temperature affected freshness impressions, but the effect was relatively slight. Environments which felt cool tended to feel fresh, yet a rise in the mean radiant temperature—which would increase the warmth of the environment—tended to produce an impression of greater freshness. At a given equivalent temperature, environments with the surroundings warmer than the air were found to be definitely fresher than cold- and neutral-wall environments. This was thought to be mainly due to the fact that the humidity of the air in the warm-wall environment was lower than that in the other two environments. Changes in humidity insufficient to affect sensations of warmth affect impressions of freshness. Under the conditions of these experiments, and to keep freshness impressions constant, a rise of 1° F. in the temperature of calm air must be compensated by a fall of about 5 % in the relative humidity.

The subjects had a distinct preference for the warm-wall environment; 73 % of them found it pleasanter than either the cold- or the neutral-wall environment.

Freshness impressions are considered to be related to transient fluctuations in the rate of heat loss from the head.

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REFERENCES

Bedford, T. (1936). The warmth factor in comfort at work. *Rep. Industr. Hlth Res. Bd., Lond.*, no. 76.

Bedford, T. (1948). *Basic Principles of Ventilation and Heating*. London: H. K. Lewis & Co. Ltd.

Bedford, T. & Warner, C. G. (1939). Subjective impressions of freshness in relation to environmental conditions. *J. Hyg., Camb.*, **39**, 498.

Munro, A. F. & Chrenko, F. A. (1948). The effects of air temperature and velocity and of various flooring materials on the thermal sensations and skin temperature of the feet. *J. Hyg., Camb.*, **46**, 451.

Vernon, H. M., Bedford, T. & Warner, C. G. (1926). The influence of cooling power and of variability of air currents on sensations of air movement. *Sp. Rep. Ser. Med. Res. Coun., Lond.*, No. 100, Pt. III.

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