FACTORS AFFECTING WARMTH COMFORT AND STUFFINESS IN DOMESTIC ROOMS

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(With 6 Figures in the Text)

INTRODUCTION

A considerable amount of work has been done since 1915 on the specification of the physical factors determining warmth comfort in large rooms, factories, offices, etc. A summary is given by Bedford (1946). Little information has hitherto been available, however, on conditions required in domestic rooms in this country, which are still heated, in most cases, by single sources of radiation.

The work on large rooms had progressed sufficiently far, by 1930, for physical standards, based in some cases on instruments specially designed for the purpose, to be laid down and even to be given legal sanction.

The most simple instrument is the ordinary mercury-in-glass thermometer. It has been shown that a temperature of 65° F. is comfortable, generally speaking, for light sedentary occupations such as office work (Bedford, 1936).

This standard is satisfactory in conditions where the radiation component is small compared with the effect of air temperature, and where there is little air movement (less than about 10 ft./min.). It has been known since 1923 (Houghten & Yaglou) that it breaks down in the following main circumstances:

(*a*) where radiant heating is used,

(*b*) in very cold weather, when heat loss by radiation to cold walls is important,

(*c*) in draughty rooms.

An attempt was made by Vernon (1932) to allow for the effects of radiation by enclosing the bulb of a mercury-in-glass thermometer in a hollow metal ball, of diameter at least 4 in. The ball is painted black, and the instrument is known as a Globe Thermometer. The physical constants of the instrument were determined by Bedford and Warner so that it could be used for the measuring of radiation. The globe thermometer shows a satisfactory agreement with human sensations in rooms which are neither draughty nor heated by single sources of radiation.

In order to allow for air movement, as well as for radiation, a device known as the Eupatheoscope was designed by Dufton (1930, 1932). It consists of a hollow blackened metal cylinder, 22 in. high, and $7\frac{1}{2}$ in. in diameter, heated internally by electric lamps, thermostatically controlled to give a surface temperature of about 75° F. The electric current to the lamps is passed through a coil surrounding the bulb of a thermometer. A high rate of cooling of the eupatheoscope causes a high time/mean consumption of current, heating the bulb of the thermometer. The latter may be calibrated experimentally, in terms of 'equivalent temperature', in conditions of freedom from radiation and draughts. While the instrument would be expected to give readings more representative of human reactions than would be given either by the mercury-in-glass or the globe thermometer, it cannot be expected to allow correctly for local heating or chilling of a stationary human subject by fires or draughts.

SCOPE OF PRESENT INVESTIGATION

The present investigation had the following main objects:

(*a*) To determine whether standards accepted for large evenly heated rooms apply to small 'domestic' rooms, and to set up new standards if necessary.

(*b*) To find the optimum contributions, as regards warmth comfort, of air heating and radiation to total warmth.

(*c*) To elucidate the physical conditions responsible for sensations of freshness and stuffiness.

PRELIMINARY WORK ON STANDARDS OF WARMTH COMFORT

Advantage was taken of tests being run by the Gas Light and Coke Co. (with the object of measuring the costs of different methods of room heating) to obtain the personal reactions of a number of observers to the comfort conditions offered. For the fuel consumption tests, several different heating appliances were run in similar rooms, the burning rate being controlled, initially, to give a constant temperature, in the centre of the room, of about 60–65° F. as measured by a globe thermometer. The globe thermometer reading was checked at least twice a day in each room against an eupatheoscope.

Subjects entering the room concerned, were allowed what time they considered necessary to acclimatize themselves,* and were then asked to estimate their warmth on the 'Bedford' scale (Bedford, 1930).

Table 1 shows the results obtained in a room heated only by convection to an equivalent temperature of 62 ± 1° F. The outside air temperature was 45–50° F.

Table 1. *Warmth sensation in convected heat*

(61–63° F. equivalent temperature)

Sensation	No. of subjects recording this sensation
Comfortable	9
Comfortably cool	3
Slightly too cool	1
Total	13

In rooms heated by fires, to the same equivalent temperatures (similarly measured) in their centres, most of the same panel of thirteen subjects complained of cold backs, and, if allowed to choose the most comfortable position in the room, sat near the fire, where the equivalent temperatures varied from 65 to 80° F., with a mean value of a little over 70°.

It was, therefore, evident that either the standard of 60–65° F. was inadequate for rooms heated by unilateral radiation, or that the instruments used were unsuitable for such rooms, or both.

ESTABLISHMENT OF TECHNIQUE FOR LARGE-SCALE TRIALS

It became clear at this stage that a considerable amount of work would be required to elucidate the physical causes of comfortable warmth in the presence of unidirectional sources of radiation. Because of the great variability of peoples' likes and dislikes, it was also evident that only means based on large samples of observers would be statistically reliable. The large number of subjects needed made it desirable to employ as short a test period as possible. Work was accordingly carried out to determine the shortest reliable test period.

For this purpose, nine subjects in turn were asked to sit in a large room heated by a fire, and to move about as necessary to keep as comfortable as possible. The air temperature in the room was kept steady. The intensity of radiation chosen as most comfortable by each subject was plotted against time. The results are shown in Fig. 1.

It will be seen that the error involved in using a test period of 5 min. instead of one of 1 hr. in determining the mean requirement of radiation for a group of nine observers is small. Comparison of the individual readings at 5 and 60 min. is given in Table 2.

* The period necessary to enable an adequate estimate of warmth comfort to be made is dealt with more fully later in this paper.

Table 2

Subject	Radiation required after 5 min. minus that wanted after 1 hr. (B.TH.U./sq.ft./hr.)
1	0
2	0
3	−2·5
4	+9·0
5	0
6	+6·0
7	+7·0
8	0
9	−1·0
Mean	+2·0

The standard deviation of the results is 4·2 B.TH.U./sq.ft./hr., giving the mean of +2·0, a standard error of ± 1·5, or confidence limits of −1·0 to +5·0 B.TH.U./sq.ft./hr. The 5 min. test period was therefore accepted, on the grounds that the errors resulting therefrom would certainly be small, and far below the random error which would be caused by reducing the number of subjects.

In comparing these results on length of test period with others already published it should be borne in mind that subjects in the present experiment had always been in a warm room engaged in their normal work for an hour or so before the test.

Desirability of radiation

A large room (30 × 15 ft.) was equipped with adjustable controlled air heating, and a gas fire at one end. 'Panels' of twenty-eight to thirty-three subjects entered the room, one subject at a time, and chose the most comfortable position, using a test period of 5 min. or longer. Measurements of air temperature, globe temperature and radiation intensity were made at the positions chosen. In this way the mean intensity of radiation desired was assessed at a number of different air temperatures.

The curve relating mean desirable globe temperature to air temperature is given in Fig. 2. It does not purport to be a curve of equal comfort, even if such a curve exists, but shows the amount of radiation of the type normally obtained from a fire the average man or woman wants at a number of different air temperatures.

Clearly, no one globe temperature can be laid down as the most desirable at all air temperatures, as would be the case if a man behaved like a copper calorimeter, and his sensations were determined by his rate of heat loss. Even when the air temperature is high enough (above 65° F.) to ensure adequate warmth without extra radiation, the subject still appears to desire radiant heat.

At air temperatures below 60° F. the mean desirable globe temperature rises again; the reason

https://doi.org/10.1017/S0022172400014145 Published online by Cambridge University Press

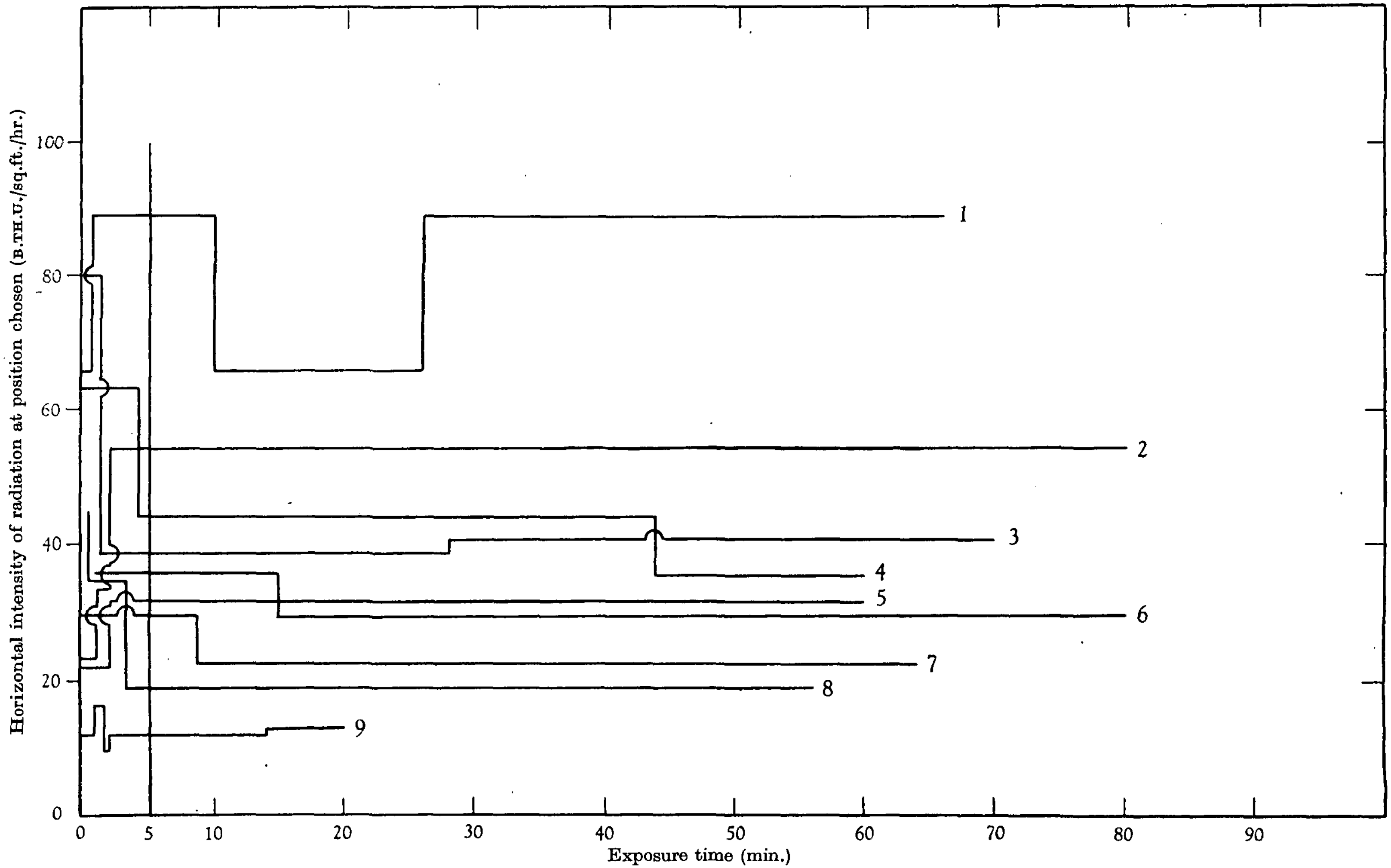

Fig. 1. To show probable error in using a test period of 5 min. instead of 1 hr.

for this became clear later on in the work described in this paper, and reported as 'minimum comfort', and is as follows. When the temperature conditions operating on the back are too low for comfort, the subject attempts to compensate for his cold back by overheating the front of his body, in such a manner that a rise of 2° in conditions affecting the front of the body 'compensates' for a fall of 1° in conditions operating on the back. At air temperatures below 60° an increasingly large proportion

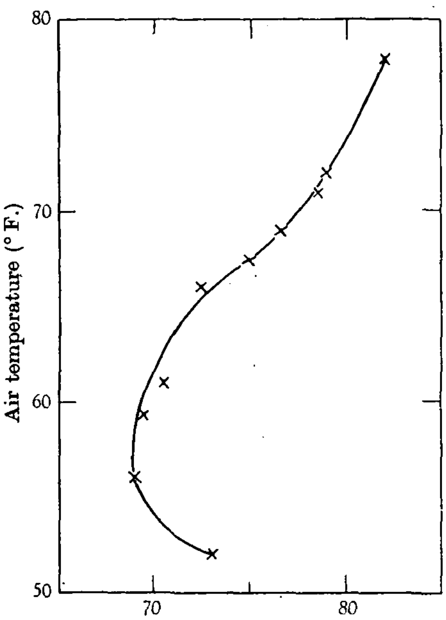

Fig. 2. To show the most comfortable globe temperature at air temperatures between 52 and 78° F.

of the subjects complained that their backs were cold, even when sitting 'on top of the fire'. When the air temperature was reduced to 52° F., no less than 96% of subjects declared themselves unable to find a comfortable position. These observations suggest that where a large proportion of the radiation is unidirectional, the sides of the subject facing towards and away from the source of heat must be treated separately, and that the cooler side must be exposed to an equivalent temperature not much less than 65°.

Design of double eupatheoscope and double globe thermometer

The desirability of measuring separately, in domestic rooms, the conditions to which the sides of the body proximal to and remote from the fire are exposed, led to the design of double eupatheoscopes and double globe thermometers, which have been described elsewhere by the present author (Yarnold, 1940). Both these instruments consist of front and back halves, each hemicylindrical or hemispherical in shape, with the flat faces apposed and insulated from one another. Each half is an independent eupatheoscope or globe thermometer.

Field work on conditions maintained in domestic rooms

Eight subjects volunteered to take readings of conditions in their own homes at times when they felt comfortable. Since they could not be expected to use bulky, complicated or conspicuous instruments, it was necessary to dispense with some information which would have been valuable, and to rely entirely on readings with the double globe thermometer. It may be taken that the mean of the reading of the front and back halves of the double globe agrees very closely in all normal conditions with the reading obtained from a single globe thermometer. The results are given in Table 3.

Despite the small number of subjects available, the conclusion may be drawn that unilateral radiation is to be regarded as an extra; its presence does not reduce, for ideal comfort, the requirement for heating the side of the body away from the fire. The widespread use of radiant heat suggests, however, that it is a very desirable extra.

Conclusions regarding ideal standards of warmth comfort in domestic rooms

It is concluded that radially symmetrical instruments are of little use for measurement of comfort conditions in rooms asymmetrically heated. Instruments must be capable of assessing separately the equivalent temperature operating on the side of the body remote from the source of heat, and this temperature should be kept to the standard level generally accepted for rooms heated symmetrically, as, for example, by 'radiators' or air-conditioning plants. This standard is 60–65° F. Over and above this, the average subject appears to desire, though he does not need, radiation to the extent of about 70 B.TH.U./sq.ft./hr.

Minimum comfort

It is a matter of common knowledge that a hot fire in a cold room offers some degree of comfort, though of a form not comparable with the 'ideal' comfort discussed in the preceding paragraphs. Work was therefore done to determine to what extent radiation supplied to one half of the body could be considered to compensate for a low equivalent temperature operating on the other half, in producing tolerable, though far from ideal, conditions.

The experimental technique was to introduce subjects singly into a room provided with a gas fire burnt fluelessly, so that there were two gradients, one of radiant intensity, and one of back equivalent temperature, both falling off with increasing distance from the fire. Subjects were asked to choose a position in which they would be prepared to sit and read for an hour or so, being as cool as possible without distinct discomfort. At each position chosen, the following measurements were made: horizontal radiant intensity, air temperature, and back and front equivalent temperature. Mean results are given in Table 4.

subjects sit at random. This 'minimum comfort' appears to be somewhat similar to Fishenden's 'comfort' (1926).

Other conclusions which may be drawn from this trial are:

(i) Minimum comfort with no radiant heat is obtained at about 60° F. equivalent temperature. This agrees with Bedford's (1936) observations and with the provisions of the Factories Act, 1937, for sedentary persons.

Table 3. *Front and back globe temperatures recorded in subjects' homes when feeling comfortable*

Subject no.	Type of heating	Mean back temp. (° F.)	S.D.	Mean front temp. (° F.)	S.D.	No. of results
1	Coke fire only	62·4	3·3	70·3	4·8	9
2	Coal fire only	67·2	3·7	72·5	2·4	60
3	Coal fire only	62·1	6·0	73·3	6·2	22
4	Gas fire only	67·5	3·8	70·8	4·3	32
Mean		65·0	—	71·7	—	—
5	Convection plus considerable radiation	63·2	3·3	71·0	6·6	4
6		60·6	4·9	67·0	5·3	20
7		64·0	4·3	66·5	4·1	26
Mean		62·6	—	68·2	—	—
8	Central heating	66·2	5·2	66·0	5·0	11
1	Flueless gas heater of low radiant efficiency	60·7	—	63·0	—	3
Mean	Mainly convection	63·5	—	64·5	—	—

Table 4. *'Minimum' comfort conditions*

No. of subjects	Dist. from fire (ft.)	Horizontal radiation intensity (B.TH.U./sq.ft./hr.)	Air temp. (° F.)	Equiv. temp. (° F.) Back	Equiv. temp. (° F.) Front	S.D. Back equiv. temp.	S.D. Front radiation intensity
12	7·4	20·4	61·8	57·8	66·0	1·6	17·2
10	10·1	22·8	61·4	57·4	66·0	1·4	18·6
7	7·6	43·6	56·6	54·5	63·1	1·7	30·3
3	6·8	71·8	58·3	55·7	67·3	—	—
17	5·6	42·6	56·8	56·5	66·8	2·2	17·9
10	5·0	81·2	55·9	56·0	69·8	1·1	28·8
10	7·1	35·1	56·9	57·0	63·7	1·9	17·7
10	8·8	19·9	59·2	58·0	64·4	0·9	14·5
10	14·5	4·6	59·0	59·3	62·4	0·8	5·3
10	8·0	16·7	57·9	57·8	64·2	0·9	8·7
10	7·4	10·7	58·3	58·7	61·7	0·8	6·3
10	10·0	17·2	56·2	55·6	59·7	1·3	16·4
10	6·0	35·1	57·4	57·4	65·1	0·9	16·7

The results are also shown in Fig. 3. From this figure, and from the negative correlation* between back equivalent temperature and standard deviation of back equivalent temperature, it will be seen that results become extremely variable at back equivalent temperatures below 56·5° F. From this it may be deduced that even 'minimum comfort' ceases to exist at lower back equivalent temperatures, and

* $r = -0{\cdot}55$, $P = 0{\cdot}09$.

(ii) About 14·5 B.TH.U./sq.ft./hr. will compensate for a fall of 1° F. in back equivalent temperature down to a back equivalent temperature of 56·5° F.

(iii) For a fall in back equivalent temperature of 1° F. the front equivalent temperature must rise about 2° F. This means that more warmth is being supplied to the body at low than at high back equivalent temperatures, which suggests that the compensation of a warm front for a cold back is psychological rather than physiological.

The physical basis of sensations of freshness and stuffiness

Though freshness is a term in very common use, it is, being a purely subjective sensation, rather difficult to define. It may be correlated, however, with measurable physical conditions of the skin, the eyes, and the mucous membrane of the nose.

The work described here was confined to study of the physical factors in the environment conducive to stuffiness and the reverse.

The relationship of freshness to warmth

It is a matter of common experience, confirmed in a general way during the work described in the first part of this paper, that freshness is associated

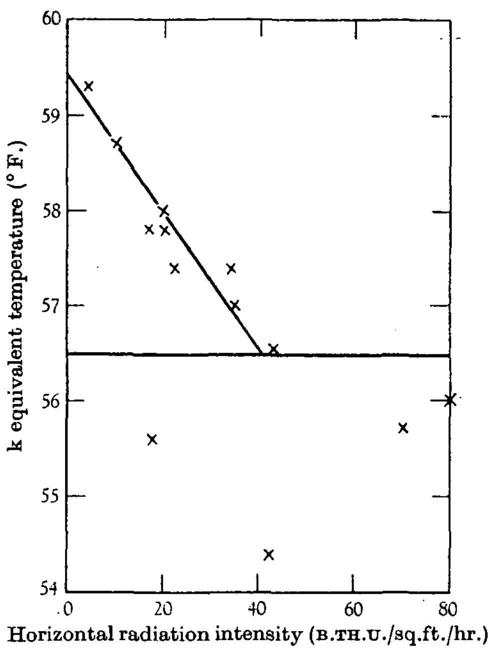

Fig. 3*a*. Compensation of radiation on front of body for cold back, to give minimum comfort.

with coolness, and stuffiness with overheating. For this reason, care was taken throughout the study described below to ensure, first of all, that the subject was entirely comfortable as regards warmth, before he was questioned on his sensations of freshness. For this reason also, the first relationship investigated was that between air temperature and freshness.

The technique was similar to that already described for the investigation of warmth comfort. A large room (30 × 15 ft.) was equipped with a high-temperature source of radiation (gas fire) at each end, and with separate means of air heating, controlled by a thermostat. An electric fan was used to modify the rate of air movement. Subjects were taken into the room, one at a time, asked to choose the most comfortable position as regards warmth, and then to state their sensations of freshness or stuffiness on the following scale:

Extremely fresh	1	Slightly stuffy	5
Very fresh	2	Stuffy	6
Fresh	3	Very stuffy	7
Neutral	4		

Measurements were also made, using a katathermometer, of the rate of air movement. Each air temperature was assessed by between seven and sixteen subjects, their sensations meaned, and the results plotted. The curve is shown in Fig. 4.

It will be seen that a clear relationship exists between air temperature and freshness, when

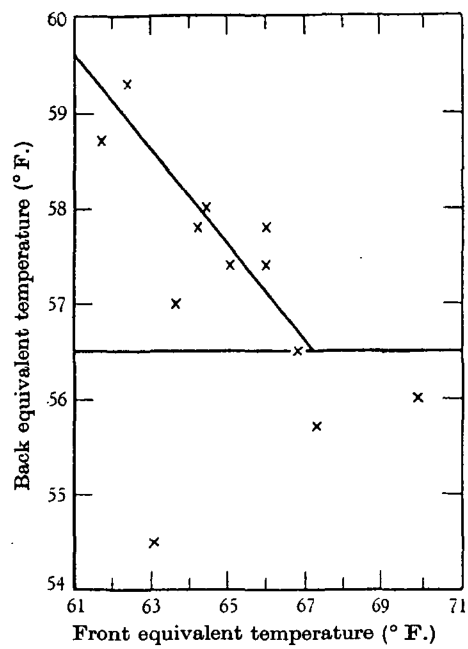

Fig. 3*b*. Compensation of high front equivalent temperature for low back equivalent temperature to give minimum comfort.

subjects are comfortably warmed. Neutral freshness occurred at about 61·5° F. An increase of 5° was sufficient to make conditions slightly stuffy, while allowing the temperature to fall to 54° F. led to slight freshness.

Effects of radiation on freshness and stuffiness

The literature contains a number of references to the alleged effect of the wave-length of the incident radiation on sensations of freshness and stuffiness (Hill, 1939; Taylor, 1933). There has been hitherto considerable controversy regarding the reality or otherwise of the effects. A reinvestigation has been made by the direct method of asking subjects to describe their sensations rather than attempting to measure their feelings as indicated, for example, by the degree to which their noses were blocked by congested mucous membrane.

For this work, a special fire was made up, whose surface temperature could be measured continuously by means of thermocouples. Subjects entered the room in turn, and took up what they considered the most comfortable position in front of the fire. For any one session of subjects, the surface temperature of the fire was kept practically constant. At the position chosen the air temperature was measured, and the subject was asked to record his sensation of stuffiness or freshness on the scale given in the previous section. With the aid of the curve in Fig. 4, it was then possible to determine an air temperature which would have raised or lowered his sensation of stuffiness to the neutral position, assuming a curve parallel to the one in the figure. For any particular surface temperature of the fire, all these 'neutral' temperatures were meaned, and the means plotted against the peak wave-length of the radiation.

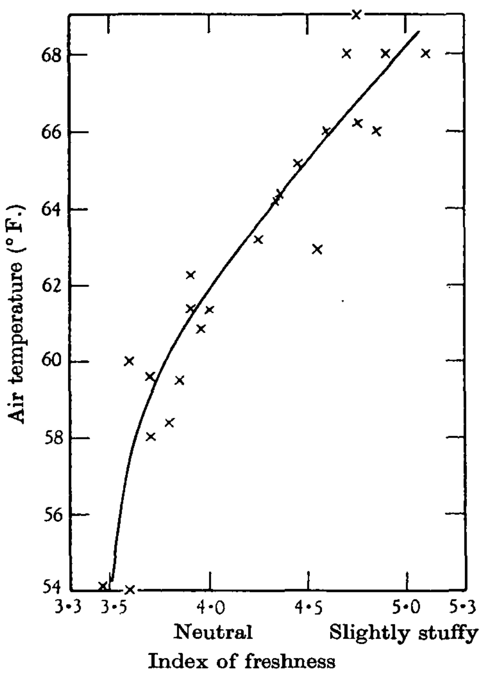

Fig. 4. Effect of air temperature on freshness. All subjects comfortable. Each point is the mean of at least 10 votes.

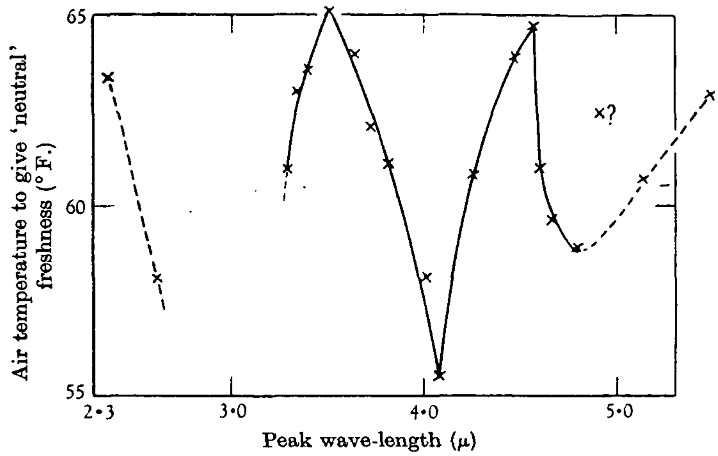

Fig. 5. Effect of radiation on freshness. Each point is the mean of at least 10 votes.

The peak wave-lengths as calculated from the surface temperatures were checked by infra-red spectrometry.*

The relationship between the peak wave-length of the incident radiation and the sensation of stuffiness or freshness is given in Fig. 5. In this graph, an air temperature of 61° F. indicates that the wave-length has a neutral effect on freshness. (To be precise, it indicates that the wave-length has the same effect as that used in the room where the results given in Fig. 4 were obtained.) An air temperature higher than this (say 64° F.) indicates that the wave-length concerned has a specific 'freshening' effect, since the air temperature could be permitted to rise to 64° F., in the presence of this radiation, without pushing the sensation of stuffiness beyond the neutral point. Similarly, temperatures below 61° F. indicate that the wave-length concerned causes stuffiness; 58° F., for example, indicates that the air temperature would have to be reduced 3°, in the presence of radiation of this wave-length, to improve the sensations of stuffiness to the neutral level.

It is evident from the curve that certain wave-lengths (about 2, 3·5 and 4·5 μ) induce sensations of freshness, whereas others (about 3, 4·1 and 4·7 μ) cause stuffiness. Considering that the radiation is not monochromatic, the effect of a small change in peak wave-length is very marked.

Physical basis of effect of radiation on freshness

Skin shows absorption bands at 3 and 4·7 μ (Taylor, 1933), caused by OH groups present in the tissues. The literature so far published, however, gives no indication of an absorption band at 4·1 μ. Measurement of the absorption

* For these measurements, the author is indebted to Mr H. D. N. Fitzpatrick.

https://doi.org/10.1017/S0022172400014145 Published online by Cambridge University Press

spectrum of silk in this region shows an absorption band at 4·15 μ (Fitzpatrick, unpublished). There is therefore evidence that those rays which penetrate skin cause freshness and those that do not cause stuffiness.

The depths of the troughs in the curve relating wave-length to stuffiness should not be expected to correspond with the depths of the troughs in the absorption spectrum, since the quantity of radiation supplied to the subjects was less at the longer wave-lengths.

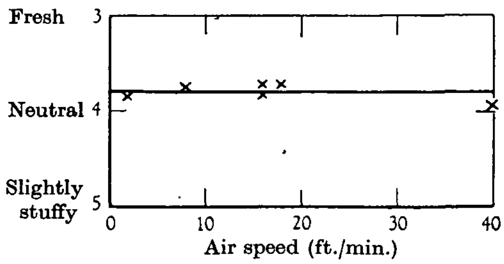

Fig. 6. The effect of air movement on stuffiness. Each point is the mean of at least 10 votes.

Effect of air movement on sensations of freshness

The effect of air movement may be gauged from Fig. 6, in which is shown the results obtained by modifying the rate of air movement with an electric fan. Evidently between almost still air, and speeds of 40 ft./min. (rather draughty conditions), the effect of air movement on sensation of freshness is negligible, provided the subject is sufficiently warm but not too hot.

GENERAL CONCLUSIONS

Warmth comfort

Measurements of comfort conditions in ordinary domestic rooms, heated non-uniformly, are only reliable if they permit separate assessment of the equivalent temperatures acting on the front of the body (assumed facing the fire) and the back. In these conditions the heat should ideally be adjusted so that the back equivalent temperature is within the range 62–64° F. The amount of radiation desired in addition to this is largely a matter of taste, but an average of 70 B.TH.U./sq.ft./hr. was found.

'Minimum comfort' may be obtained down to back equivalent temperatures of about 56·5° F. on the basis of a rise of 2° front equivalent temperature or 14·5 B.TH.U./sq.ft./hr. compensating for a fall of 1° in back equivalent temperature.

Freshness and stuffiness

Providing a subject is comfortable as regards warmth, feelings of stuffiness are caused mainly by excessive air temperature, which, in the absence of radiation of suitable wave-length, should not exceed 61° F. Those wave-lengths which are not absorbed by the skin (i.e. 2, 3·5 and 4·5 μ) induce sensations of freshness, while those which are absorbed (3, 4·1 and 4·7 μ) cause feelings of stuffiness. Provided warmth comfort is satisfactory, sensations of freshness and stuffiness are unaffected by any normal speeds of air movement.

SUMMARY

One object of the investigation was to determine the ideal contributions to warmth comfort in small 'domestic' rooms of air heating and radiation. It was soon found that in rooms heated by fires, subjects usually complained of cold backs when the equivalent temperature was in the region of 60–65° F., the accepted standard for buildings heated by convection, and preferred equivalent temperatures above 70° F.

Since large-scale trials, using many observers, were clearly necessary, the reliability of 5 min. test periods was studied; these short periods were proved reliable so long as the subject had previously been in a comfortable room for an hour or so.

It was found necessary, in rooms heated by fires, to treat separately the side of the subject facing the fire and remote from it. The cooler side must be exposed to an equivalent temperature not much less than 65° F., while radiation falling on the warm side is to be regarded as a very desirable, but non-essential, bonus. These conclusions were confirmed by field work in the subjects' own homes.

The eupatheoscope and globe thermometer were modified to enable conditions acting on the two sides of the body to be assessed separately.

The extent to which radiation acting on the front of the body could compensate for a cold back to produce what was called 'minimum comfort' was also studied. It was shown that down to back equivalent temperatures of about 56° F. an increase of 2° in front equivalent temperature will compensate for a fall of 1° in back equivalent temperature, but below 56° F. compensation fails.

The physical basis of sensations of stuffiness and freshness were also investigated. Throughout these experiments care was taken to ensure that the subjects were neither too hot nor too cold. In these conditions, only two factors appear to be important. First, the air temperature should be as low as possible. To obtain warmth comfort with a low air temperature some high temperature source of radiation is generally necessary. The peak wave-length of the radiation emitted by the fire is also of great importance, a striking change in the personal sensations occurring, for example, as the wave-length increases from 2 to 3 μ. In general, those wave-lengths which are absorbed in the outer layers of the skin cause sensations of stuffiness, and those which are not give rise to feelings of freshness. Peaks at 3, 4·1 and 4·7 μ should therefore be avoided in the design of gas and electric fires.

https://doi.org/10.1017/S0022172400014145 Published online by Cambridge University Press

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(*MS. received for publication* 18. VI. 47.—Ed.)