RADIATIVE AND CONVECTIVE STIMULI OF THRESHOLD INTENSITY

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(With 7 Figures in the Text)

One's impressions of the freshness or stuffiness of an environment depend on the stimulation, or lack of stimulation, of exposed areas of skin, mainly by thermal changes. Bedford & Warner (1939) found that their own impressions of freshness were strongly influenced by the variability of air movement, even when the temperature and the average speed of the air were held constant. Their results were based on field observations; since more precise information might be gained from an experimental approach, including quantitative information of immediate practical value to engineers, these investigations of the effects of both convective and radiative stimuli were planned.

The first of these, dealing with the intensities of stimuli which would just suffice to produce thermal sensations, is reported in this paper.

Earlier workers have ascertained the threshold intensities of radiant-heat stimuli (Hardy & Oppel, 1937; Ebaugh & Thauer, 1950), but there are no similar data for convective stimuli. Radiative and convective stimuli were studied for the same experimental subjects in this investigation.

First the threshold intensity of radiation necessary to evoke sensations of warmth was determined for different areas of the skin of the face and forehead. This allowed comparison with previous studies. Later the influence of air movement and increased air temperature on threshold conditions was examined, and an equation was derived relating air temperature with air speed.

APPARATUS

The experiments were conducted in a cubicle, 8 ft. by 8 ft. by 12 ft. high, in which the air temperature could be controlled to within $\pm\frac{1}{2}°$ C. The surface temperature of the walls was not controlled, but closely followed the air temperature. The air inlet to the cubicle extended over the entire ceiling, so that the air speed inside the cubicle was of the order of only 12 ft./min. The atmospheric humidity was not controlled. Throughout the experiments, the air temperature was maintained at a comfortable level of about 19° C. (66·2° F.).

The apparatus used to provide the stimuli was of two kinds. In the earlier experiments, the radiation threshold was determined for an area of skin of 30 cm.^{2} or less. A blackened metal disk attached to the heating element of an electric bowl fire acted as the radiant source. The reflector was screened from the subject by a hardboard screen and the radiation passed through holes in three polished aluminium plates, the middle plate carrying a shutter, and the one nearest the

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subject having a variable aperture so that areas of from 5 to 30 cm^2. could be exposed. The intensity of the radiation at the surface of the skin could be varied by sliding the source closer to or farther from the subject, or by altering the supply voltage to the heater through a Variac transformer.

When it was required to stimulate a larger area of skin, not only with radiation, but also with moving air at a temperature at or above the general temperature within the cubicle, apparatus took the form of a small wind tunnel. A heater was inserted before the fan to warm the air passing through the wind tunnel without exposing the skin of the subject to radiation. Several gauze straighteners were incorporated in the body of the tunnel, the last being an electric wire heating mat, which was used as a source of radiant heat when required.

PROCEDURES

The experiments were carried out by two persons only, acting in turn as experimenter and subject. The intensity of the radiation was measured at the position of the exposed area of skin by means of a calibrated thermopile and galvanometer. When radiation and air movement were present at the same time, a fluorite window was used to shield the thermopile. The thermopile was also used to measure the skin temperature. The temperature of the air issuing from the wind tunnel was measured with a fine thermocouple, and its speed by means of a hot wire anemometer.

Before any experiments were carried out the subject sat in the cubicle until he had become accustomed to the environment and had been perfectly comfortable for at least 10 min. He was then exposed to a series of thermal stimuli, each of 5 sec. duration, which were presented as a regularly graded series, starting with a stimulus of high intensity, or one only slightly above the environmental level, and proceeding by steps of about $\frac{1}{2}$° C. to the other extreme value, in accordance with the limiting method much used in psycho-physical experiments. After each exposure the subject said whether or not he had experienced any thermal sensation. Several such series of observations were carried out for each condition and each subject. The intensity of the stimulus was measured after each exposure, and recorded along with the subjective appraisal of the condition.

For the experiments where radiation was used to provide the thermal stimulus, the probit method of statistical analysis has been used. This method, described by Finney (1952), is of much value in the determination of the median effective stimulus, when the response is of the quantal, or 'all-or-none', type. The changes in radiation intensity were small and the responses were variable, and it was thought that the median effective stimulus would be determined more reliably by the probit method than by taking the mean of a series of individual thresholds obtained by the usual limiting method.

When the stimulation was by warmed and moving air the threshold was taken as the temperature at which the response changed from one of no detectable change to a definite sensation of warmth. On a few occasions the responses of the subjects to the individual stimuli were so variable that it was not possible to determine a value for the threshold.

RESULTS

(1) *General*

Three methods were used to evoke a sensation of warmth at the threshold level: (1) by increasing the intensity of the radiant heat falling on the skin over that from the solid surroundings of the cubicle by an amount which was just sufficient to evoke a sensation of warmth, and obtaining values of such threshold intensities for various areas of skin; (2) by exposing the skin to a stream of air moving at one of several velocities and determining the increase in air temperature above that in the cubicle required to evoke a sensation of warmth; and (3) by increasing the intensity of the radiation falling on the skin, and simultaneously exposing the skin to a stream of moving air.

The first method presented no difficulty, but in the other two series, owing to limitations in the apparatus, a complete dissociation of the variables was not possible.

In order to maintain a stable air temperature in the experiments with warmed air, the air was passed through the tunnel continuously and deflected from the skin by a shutter, except during the required period of exposure. The temperature of the internal surfaces of the tunnel was thus raised slightly and constituted a weak source of radiation; the amount of heat required to evoke a sensation was so small that this increase in radiant temperature was a significant factor in the production of a sensation of warmth. In fact, although the stream of air was warmed with the intention of thus reducing the convection loss from the skin and thereby evoking a sensation of warmth, the combination of air speed and temperature was such that the rate of heat loss by convection was actually increased.

In the third method when the air passed through the electric heating mat the increase in its temperature was greater than had been anticipated, and this also was a significant thermal factor.

Because of these effects the results, although they will be presented under three separate headings, have had to be treated as two groups, one where warming was by radiation alone, and the other where changes in radiation, air temperature and air movement acted simultaneously.

(2) *Exposure to radiation*

In this section the results of experiments designed to determine the threshold intensity of a radiation stimulus (cal./cm.^{2}/sec.) for the production of a sensation of warmth for four areas of different sizes on the forehead and face will be described. The duration of each exposure was 5 sec.

These results were examined by the probit method, and regression equations relating the probit value and the intensity of the stimulus were computed.

(*a*) *Area of* 30 *cm.*^{2}

The largest area which could be stimulated by means of the first of the assemblies of apparatus which were described in a previous section (p. 32), was 30 cm.^{2}. The threshold for that area was determined first, and that for a smaller area (15 cm.^{2})

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afterwards, since previous experience had shown that subjects encountered considerable difficulty at first in deciding with consistency whether or not a stimulus of about the threshold intensity had evoked a sensation; it was thought that this difficulty might be less if a relatively large area were exposed in the initial experiments.

When a probit regression equation was computed from the results for subject I, there was a considerable scatter of the points around the line, and also an unexpectedly high proportion of positive responses to stimuli of low intensity. This

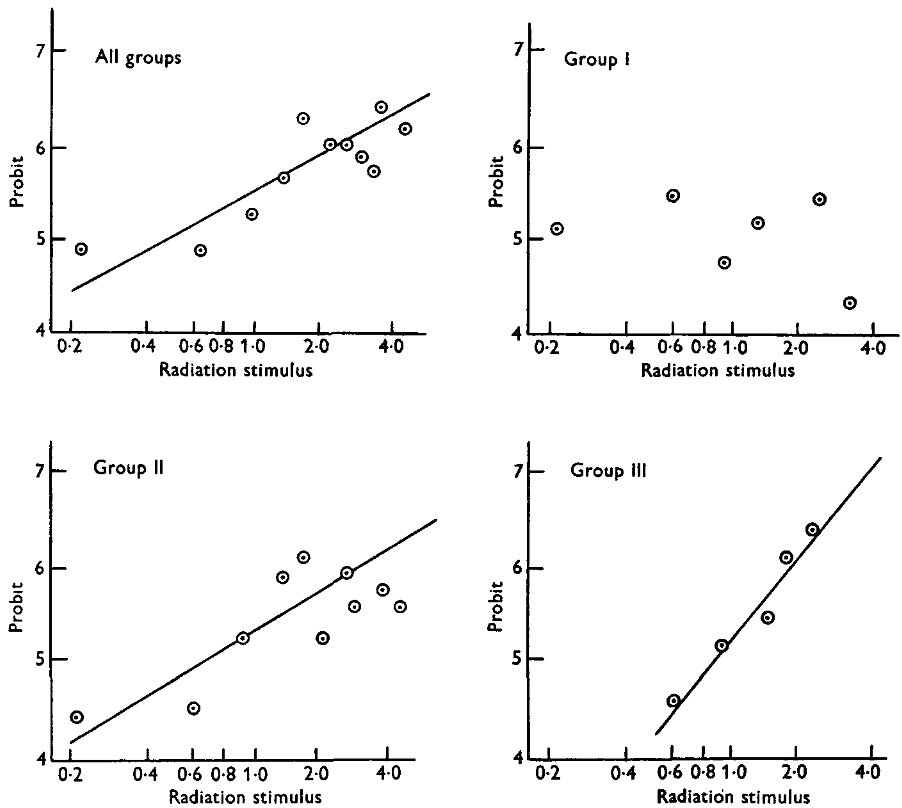

Fig. 1. Response curves for subject I for exposure of an area of 30 cm.^{2} to radiation. Radiation stimulus is represented on a logarithmic scale in terms of cals./cm.^{2}/sec. $\times 10^3$.

seemed to indicate that the subject, who had been required to make a definite reply after each exposure, had at times been so uncertain, particularly at the lower intensities, that his replies were little better than guesses. In order to determine whether or not his ability to discriminate had improved with time and practice, the results from this subject were divided into three groups of approximately equal size, for experimental days 1–4, 5–10, and 11–14. The data for each of these groups were analysed separately and the regression diagrams are shown in Fig. 1.

A diminishing degree of scatter of the points round the regression lines with time is apparent, and values of χ^2 for the various groups confirm this improvement.

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The regression coefficient for the first group is clearly insignificant, while those for the second and third groups are significant. In the light of this demonstration of the improvement in the subject's discrimination with time, it is reasonable to regard the threshold intensity from group III, 0·00083 cal./cm.^{2}/sec., as the truest estimate of the threshold for this area of exposure.

The results of the exposures of subject II were also divided into three consecutive groups. The regression diagrams showed that this subject's ability to discriminate warmth sensations did not improve with time. The value of χ^2 for the third group was so high, and the regression coefficient so insignificant, that there was clearly no evidence of any association between intensity of stimulus and probit values, even in this group. Many more experiments were made on this subject than on subject I—594 compared with 282—but there was no apparent improvement in his discernment of sensations.

This difference between subjects will be discussed more fully later. Because of the variability of the results for subject II with this area of exposure, no further experiments were made on him with the smaller area of exposure.

(*b*) *Area of* 15 *cm.*^{2}

The results for subject I when the area of exposure was only 15 cm.^{2} showed very little scatter about the regression line, indicating that he had benefited from his previous experience with the larger area of exposure, and had maintained his ability to discern sensations of warmth with a fair degree of certainty. The value of χ^2 for the regression line, 8·3, is insignificant at the 0·05 level. The threshold intensity determined from this regression equation was 0·0014 cal./cm.^{2}/sec., compared with 0·00083 cal./cm.^{2}/sec. for an area of 30 cm.^{2} with this subject. The difference between these values is not statistically significant.

(*c*) *Area of* 70 *cm.*^{2}

When the area of skin stimulated was 70 cm.^{2}, the threshold intensity of stimulus for subject I was 0·00023 cal./cm.^{2}/sec., and the data for this subject could be well fitted by a regression equation.

The data for subject II were fitted less well by a probit regression equation, and the value of χ^2 for this equation, 15·3, is significant at the 0·05 level, but there were only four degrees of freedom. It therefore seems that this subject still had difficulty in discerning sensations with confidence at intensities of stimulus close to the threshold, even with this larger area of exposure, although the results this time showed a clear trend. A threshold value of stimulus was calculated, and allowance made in the determination of the standard error for the high value of χ^2 and the low number of degrees of freedom. The value of the threshold was 0·00012 cal./cm.^{2}/sec. This value appears to be considerably lower than the corresponding threshold value for the other subject, but the standard error was very much greater.

(*d*) *Area of* 200 *cm.*²

When the area stimulated was increased to 200 cm.², the threshold intensity of stimulus for subject I, determined from the regression equation which fitted the data well ($\chi^2_{(10)} = 8{\cdot}9$), was reduced to 0·000123 cal./cm./sec. With the same area of stimulation the threshold intensity of subject II was 0·000058 cal./cm².sec., and the regression coefficient was significant at the 0·05 level of probability ($\chi^2_{(5)}$ being 7·7).

Again, the threshold intensity for subject II was considerably lower than that for subject I. The regression line for the data for the former subject was significant in terms of the χ^2 test, although the value of P was less than that for the data for the other subject. Again the standard error of the threshold for subject II was greater than that for subject I, which tends to suggest that the disparity between the two threshold values may be more apparent than real. As they stand, the threshold values found for subject II with the various areas of stimulation seem to indicate that this subject could not discern sensations of warmth with any reliability until the area of exposure was considerable, but with the larger areas of exposure his sensitivity was somewhat greater than that of the other subject.

Table 1. *Results of experiments where stimulation was by radiation for both subjects*

Area of exposure (cm.²)	Threshold intensity (log)	Standard error (log)	Probit regression coefficient	S.E.	χ^2	Degrees of freedom	Threshold intensity (cal./cm.²/sec.)
			Subject I				
30 (1)	—	—	−0·41	±0·40	9·81	7	—
30 (2)	−3·12	±0·17	1·62	±0·35	7·73	10	0·00076
30 (3)	−3·08	±0·15	3·18	±1·01	0·37	3	0·00083
30 (all groups)	−3·27	±0·18	1·31	±0·24	10·97	10	0·00054
15	−2·85	±0·08	2·28	±0·38	8·29	9	0·0014
70	−3·63	±0·06	3·73	±0·43	7·44	6	0·00023
200	−3·91	±0·15	1·41	±0·22	8·94	10	0·000123
			Subject II				
70	−3·92	±0·28	2·50	±0·40	15·26	4	0·00012
200	−4·24	±0·32	1·14	±0·26	7·72	5	0·000058

The results obtained from all the experiments described above are summarized in Table 1.

(*e*) *Variation of threshold intensity with area stimulated*

Fig. 2 shows the threshold intensities for subject I plotted in relation to the area of skin stimulated. For areas less than about 100 cm.² there is an approximately linear relation between the logarithms of area and threshold intensity.

The difficulty experienced in determining threshold values for subject II makes it impossible to present a similar summary of data for him. However, such of his results as appear to be reliable show a general agreement with the data for subject I, but with a tendency to rather lower threshold values.

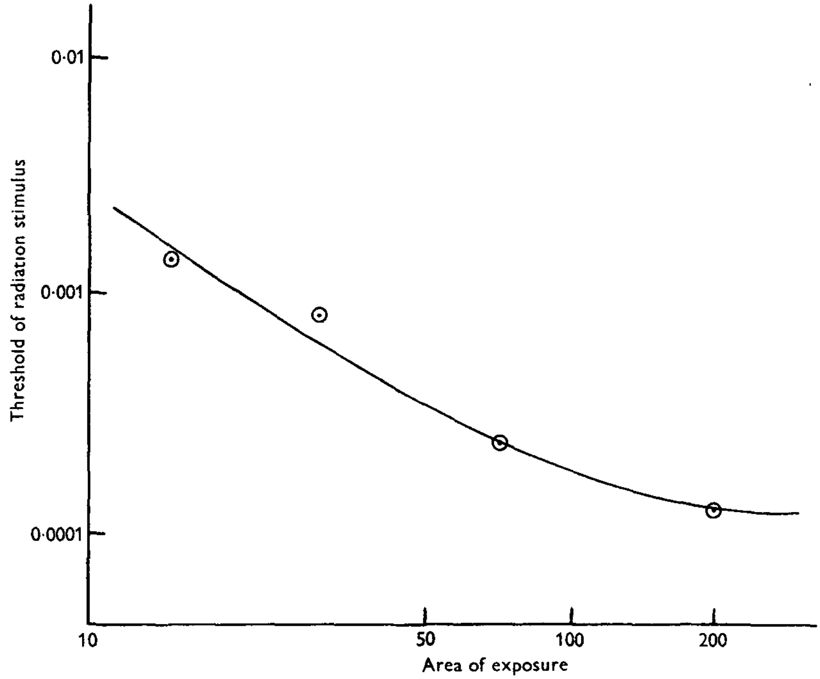

Fig. 2. Radiation stimulus (cal./cm.²/sec.), against area of skin exposed (cm.²), for subject I. Logarithmic scales.

(3) *Exposure to warmed moving air*

The results to be considered under this heading relate to experiments in which the thermal stimulus was provided by a stream of warm air from the small wind tunnel previously described.

The threshold air temperatures were determined by the limiting method. The subject was exposed to a current of air, the speed of which was kept constant throughout a given series of exposures, and the temperature varied between one exposure and the next. Each exposure was of 5 sec. duration, and the area of skin exposed was 200 cm.² Thresholds were determined for each of the two subjects with air speeds of 35, 50, 65, 90 and 100 ft./min. The skin temperature on the forehead was measured after each exposure.

In some experiments, when the air temperature was low and the cooling effect of the air movement predominated over the slight warming due to the small elevation in air temperature, sensations of coolness were evoked. The subjective responses were accordingly recorded as of warmth, or of coolness, or, on some occasions, of no detectable thermal change.

The data summarized in Table 2 reveal that the threshold values of the air temperature required to evoke sensations of (*a*) warmth, and (*b*) coolness, in subject II, with an air speed of 35 ft./min.—21·5 and 20·7° C. respectively—were very slightly higher than the corresponding values—21·1 and 20·5° C.—for subject I. At all higher speeds, however, the values for subject II were lower than the values for subject I, and the rate of increase of the threshold air temperature with air speed was also less.

The comparable threshold temperatures for warmth sensations for subjects I and II at air speeds of 50, 65, 90 and 100 ft./min. respectively were 22·4 and 21·8, 23·2 and 22·2, 24·0 and 22·7, and 24·8 and 23·3° C. The threshold values for sensations of coolness under similar conditions were 21·3 and 21·0, 22·2 and 21·4, 23·0 and 22·2, and 23·9 and 22·5° C.

Table 2. *Results of experiments where stimulation was by 'warmed moving air', for both subjects*

(*ta*, mean threshold air temperature, ° C.; Δta, increment in air temperature, ° C.; calc. ΔR, calculated change in radiation intensity, cal./cm.²/sec.; calc. ΔH_c, calculated change in convective heat loss, cal./cm.²/sec.)

Subject I

	Warmth					Coolness			
Air speed (ft./min.)	No. of thresholds	*ta*	Δta	Calc. ΔR	Calc. ΔH_c	No. of thresholds	*ta*	Δta	Calc. ΔR
35	17	21·1 ± 0·6	2·1	0·000206	0·000083	16	20·5 ± 0·3	1·5	0·000165
50	17	22·4 ± 0·5	3·4	0·000318	0·000195	13	21·3 ± 0·2	2·3	0·000235
65	13	23·2 ± 0·6	4·2	0·000375	0·000252	18	22·2 ± 0·5	3·2	0·000305
90	21	24·0 ± 0·9	5·0	0·000402	0·000279	21	23·0 ± 0·8	4·0	0·000346
100	8	24·8 ± 0·6	5·8	0·000445	0·000322	8	23·9 ± 0·9	4·9	0·000402

Subject II

	Warmth			Coolness		
Air speed (ft./min.)	No. of thresholds	*ta*	Δta	No. of thresholds	*ta*	Δta
35	12	21·5 ± 0·5	2·5	12	20·7 ± 0·7	1·7
50	7	21·8 ± 0·4	2·8	7	21·0 ± 0·3	2·0
65	18	22·2 ± 0·7	3·2	17	21·4 ± 0·6	2·4
90	13	22·7 ± 0·2	3·7	15	22·2 ± 0·3	3·2
100	10	23·3 ± 0·5	4·3	10	22·5 ± 0·5	3·5

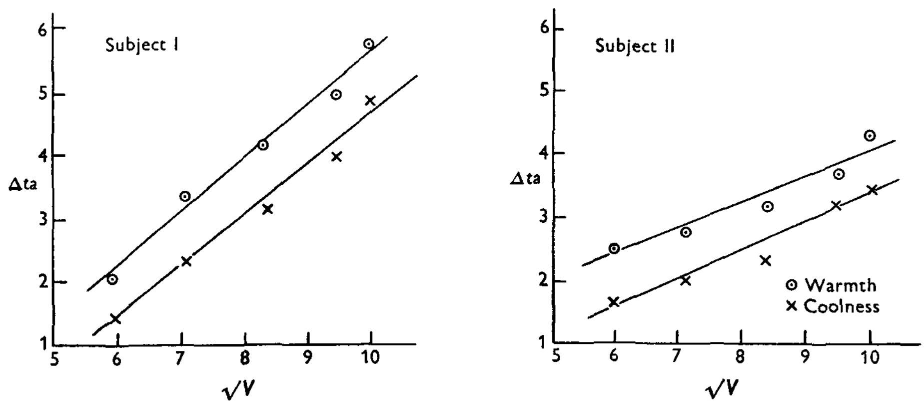

Fig. 3. Threshold values of the increase in air temperature (Δta °C.) against the square root of the air speed ($\sqrt{V}$ ft./min.) for sensations of warmth and coolness.

Fig. 3 shows the thresholds for the two subjects in terms of increases above ambient temperature, plotted against the square root of the air speed. In both instances the relationships are essentially linear and the slopes of the regression

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lines for sensations of warmth and of coolness agree well for either subject. The coefficients of the regressions of change in air temperature on the square root of the air speed are 0·84 and 0·79 for sensations of warmth and coolness respectively for subject I, and 0·41 and 0·45 for subject II.

In these experiments it was necessary to take account of the increase in the radiant temperatures of the walls of the wind tunnel owing to the passage of the warmed air. The values of this change, at the position of the subject's head, associated with the threshold air temperatures for subject I have been included in Table 2, and these are used later in the calculation of a heat loss equation.

(4) *Exposure to radiation in the presence of moving air*

In the experiments designed to investigate the effect of a stream of air at approximately room temperature upon the production of a sensation of warmth by radiation, the thermal stimulus was provided by using the wind tunnel, with the wire heating mat at its delivery end as the source of radiation. The area of skin exposed to the radiation was again the whole face and forehead, some 200 cm.².

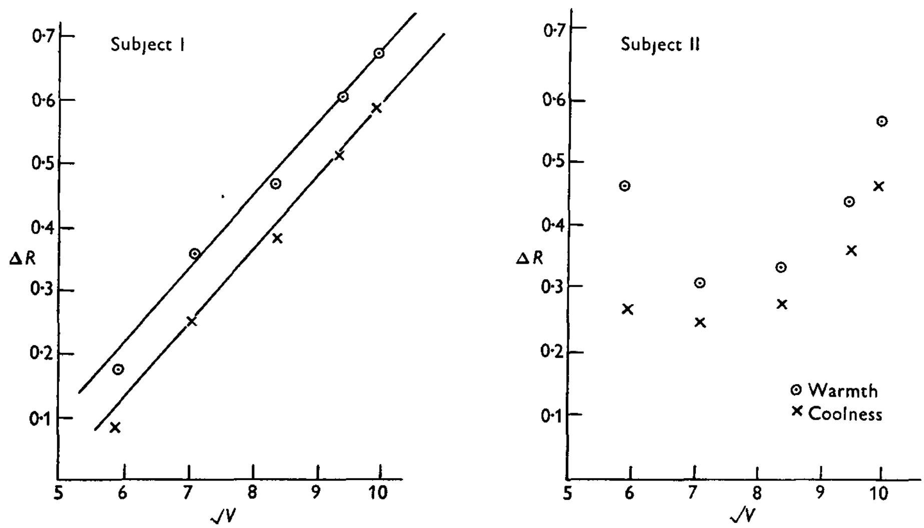

Fig. 4. Threshold values of the increase in radiation intensity (ΔR, cal./cm.²/sec. $\times 10^3$) against the square root of the air speed ($\sqrt{V}$ ft./min.) for sensations of warmth and coolness.

In a given experiment the air speed was kept constant at one of a series of predetermined values, namely, 35, 50, 70, 90 and 100 ft./min. After each exposure the radiation intensity, the temperature of the air stream, and the skin temperature on the forehead were measured. The increase in the temperature of the air stream was greater than had been expected, and had to be taken into account in the subsequent derivation of a heat-loss equation. As in the previous series of experiments, sensations of coolness were reported by the subjects, and threshold conditions for evoking such sensations, as well as sensations of warmth, have been determined.

The threshold intensities of the increase in radiation intensity determined by the probit method at various air speeds for the two subjects are shown in Fig. 4.

For subject I the regression coefficients were 0·000116 and 0·000119, for sensations of warmth and of coolness respectively. Thus the change in radiation intensity necessary to compensate for a unit change of $\sqrt{V}$ was practically identical for both kinds of sensation, as one would expect.

In the results for subject II certain irregularities are apparent. The values of the threshold intensities of radiation when the air speed was 35 ft./min. (0·000468 and 0·000275 cal./cm.²/sec. for sensations of warmth and of coolness respectively) were considerably higher than those when the speed was 50 ft./min. (0·000316 and 0·000251 cal./cm².sec.), and thereafter the thresholds increased as the air speed increased. As in the previous series of experiments, the thresholds at these higher speeds were less than the corresponding thresholds for subject I. Even if the threshold values when the air speed was 35 ft./min. ($\sqrt{V} = 5{\cdot}92$) are ignored, the remaining points do not lie on linear regression lines. This would appear to be explicable only by the difficulty which this subject experienced in discerning the effects of a radiative stimulus.

Table 3. *Results of experiments where stimulation was by 'radiation and moving air' for both subjects*

(ΔR, increase in radiation intensity, cal./cm.²/sec.; *ta*, temperature of air stream, ° C.; calc. ΔH_c, calculated change in convective heat loss, cal./cm.²/sec.)

Air speed (ft./min.)	Subject I: Warmth ΔR			Subject I: Coolness ΔR		Subject II: Warmth ΔR	Subject II: Coolness ΔR
	ΔR	*ta*	Calc. ΔH_c	ΔR	*ta*	ΔR	ΔR
35	0·000178	20·54	0·000055	0·000087	20·04	0·000468	0·000275
50	0·000363	21·07	0·000240	0·000251	20·54	0·000316	0·000251
70	0·000468	21·86	0·000345	0·000380	21·52	0·000339	0·000282
90	0·000603	22·39	0·000480	0·000513	22·07	0·000437	0·000363
100	0·000676	22·50	0·000553	0·000589	22·21	0·000575	0·000468

In the first series of experiments, when the air temperature remained constant at 19° C., the air was calm (speed 12 ft./min.), and an area of skin of 200 cm.² was stimulated by radiant heat, the threshold value of the radiation stimulus required to evoke a sensation of warmth on subject I was 0·000123 cal./cm.²/sec. In the experiments described in this section, when a radiative stimulus was applied simultaneously with an increase in the air speed, a greater intensity of radiation was required. With air speeds of 35, 50, 70, 90 and 100 ft./min. respectively, the threshold values of the increase in radiation were 0·000178, 0·000363, 0·000468, 0·000603 and 0·000676 cal./cm.²/sec. With the same air speeds and somewhat lower radiation intensities, sensations of coolness were evoked, the threshold intensities being 0·000087, 0·000251, 0·000380, 0·000513 and 0·000589 cal./cm.²/sec. respectively.

As has been mentioned above, the passage of the air over the heating mat, which was the source of radiation in these experiments, caused some increase in the temperature of the air stream. That increase depended on the intensity of radiation and on the air speed. The changes in radiation intensity and the associated changes in air temperature at which sensations of warmth and of coolness were evoked at the various air speeds are shown in Table 3.

DISCUSSION

(1) *Differences between the subjects*

Differences between the responses of the two subjects have been noted. The results for subject II indicated repeatedly that he was not capable of discerning consistently the small thermal sensations ordinarily associated with a stimulus of low intensity. Previous workers (Rubner, 1897; Hardy & Oppel, 1937) have remarked upon the vague and fleeting nature of such sensations.

In the earliest series of experiments there was no improvement in the response curves for subject II with time, and not until the area of exposure was increased considerably was there any indication of a reliable value for the threshold. Then the threshold values obtained were lower than those for the other subject, but statistical considerations of the relative standard errors indicate that the true threshold for the two subjects could have been very similar. Likewise, when the stimulation was by warmed moving air, the threshold values for subject II at the higher air speeds were somewhat lower than those for subject I, and further inconsistency was also noted in the last group of experiments with a radiative stimulus in the presence of air movement.

Because of these irregularities, explicable only on the grounds of subjective variability, all the calculations which follow have been based on the results for subject I. Although the results obtained on this one subject may not represent the average values for a large population, that may not invalidate general conclusions on the relative effects of the various factors.

(2) *Stimulation by radiation*

In all the experiments where stimulation was by radiation, the temperature of the radiant source was very low and the wavelength of maximum intensity of the emitted radiation of the order of 10μ. Hardy (1934) has shown that the human skin behaves essentially as a black body at such wavelengths.

The results for subject I in this investigation are compared with the data obtained by Hardy & Oppel (1937) in a similar study, in Fig. 5. The agreement is remarkably close, and such disparity as is apparent may be due to a difference in the criteria used to define the threshold intensity. The threshold value obtained by Hardy & Oppel for an area of 200 cm.^{2} was 0·00021 cal./cm.^{2}/sec., compared with 0·000123 cal./cm.^{2}/sec. in the present study, but a value of 0·00021 cal. would have resulted in the experiments here described if a response rate of 62 % instead of 50 % had been taken as the criterion.

Ebaugh & Thauer (1950), from experiments in which they exposed the whole of the anterior body surface above the waist to a radiation stimulus, but always referred sensations to the forehead, quote a figure of 0·00032 cal./cm.^{2}/sec. for the threshold intensity. Hence there is reasonable agreement between the present results and earlier findings.

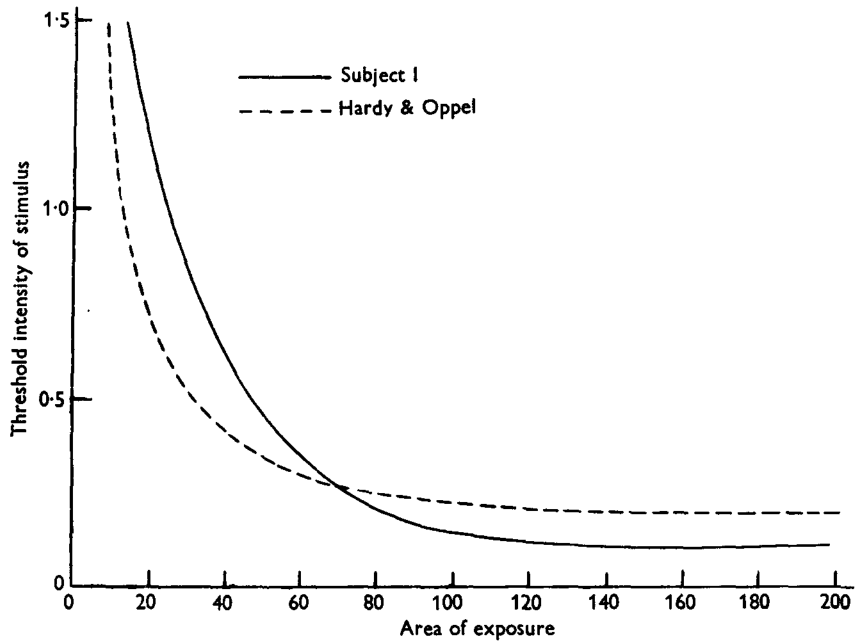

Fig. 5. Comparison of the results for subject I with similar results of Hardy & Oppel. Stimulation by radiation alone. Intensity of stimulus, cal./cm.²/sec. × 10³, area of exposure cm.².

(3) *An equation for heat loss by convection*

From the results of the experiments where radiation alone was used as a thermal stimulus, it has been estimated that the production of a sensation of warmth was associated with a decrease in the rate of heat loss from the skin of 0·000123 cal./cm.²/sec. when the area to which the stimulus was applied was 200 cm.² of the face and forehead. From the other experiments a series of values has been obtained of the changes in radiation, air temperature and air speed which were associated with the production of a similar sensation. On the assumption that under such circumstances the combined effect of these thermal factors would have resulted in a similar change in the rate of heat loss from the face and forehead, the changes in these factors have been further examined in an attempt to derive a relationship between the effects of the temperature and speed of the air on the rate of convective heat loss. It must be borne in mind, of course, that the values of the various thermal factors used in these computations are based on subjective assessments, and therefore lack the precision of physical estimates, and thus an equation derived from these results will not provide as exact a definition of the effects of the simultaneous action of the various factors as would a physical examination of a similar problem. Further, when the total change is only of the magnitude found here, a very small absolute difference in the rate of heat loss may appear as a considerable proportional difference. It was with these reservations clearly in mind that the data were examined.

As a basis for further calculation it was also assumed that, since the experiments were all conducted in an environment considerably cooler than that in which the onset of active sweating could be expected, the heat loss by the evaporation of insensible perspiration was constant; and that the equation most likely to define the rate of heat loss by convection would be of the form:

$$H_c = a\sqrt{V}\theta,$$

where H_c is the rate of heat loss by convection, V the air speed, θ the difference between the temperature of the air and that of the surface of the skin, and a a constant.

Without assuming some suitable value for the constant in such an equation, it is impossible to arrive at a value for the rate of heat loss by convection under the conditions in the standard environment when no sensation was evoked, but since this environment was maintained virtually constant the rate of heat loss in those conditions should also have been constant, and thus a term k can be introduced into the proposed equation to account for this unknown basic rate of heat loss. Then the equation for the rate of heat loss by convection becomes

$$\Delta H_c = a\sqrt{V}\theta - k, \tag{i}$$

and since ΔH_c, $\sqrt{V}$ and θ are known, a and k may be determined.

Fig. 6 shows the relation between the calculated change in convective heat loss and the product $\sqrt{V}\theta$ for conditions evoking a sensation of warmth, whence can be derived the equation

$$\Delta H_c = 0{\cdot}000018\sqrt{V}\theta - 0{\cdot}00089, \tag{ii}$$

where ΔH_c is the change in convective heat loss in cal./cm.^{2}/sec., V is the air speed in cm./sec., and θ is the skin-air temperature difference in °C.

The subtracted constant in equation (ii), 0·00089, is the value k, representing the rate of heat loss in the standard environment where the air temperature was 19° C., the average skin temperature about 33·5° C. and the air speed 6 cm./sec. From the equation the value of $a\sqrt{V}\theta$ for these conditions would be 0·00064 cal./cm.^{2}/sec., which is less than the expected value of 0·00089, but it will be shown later that differences between the types of air movement in the standard conditions and when air issued from the small wind tunnel probably account for the discrepancy.

(4) *Sensations of coolness*

In some of the experiments, where the stimulus was made up of the simultaneous effects of radiation, air movement and elevated air temperature, the cooling effect of the air movement was so much in excess of the warming due to the other factors that the subject reported a sensation of coolness. Since it had not originally been intended to investigate sensations of coolness, the observations on these sensations were noted, as it were, in passing, and no data were obtained on their production by a stimulus of radiation alone. But although the threshold for sensations of coolness in terms of increased heat loss is not known precisely, calculations can be made to estimate the value of the convection coefficient from the data which are available.

For the experiments where moving air was one of the stimulating factors, the values of $\sqrt{V}\theta$ and the change in heat loss due to radiation associated with the

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production of a sensation of coolness have been determined. Again assuming that the evaporative heat loss remained constant, and that the total change in heat loss needed to evoke a sensation was also constant, the conditions may be represented as

$$\Delta H_R + \Delta H_c = K, \tag{iii}$$

where ΔH_R is the change in heat loss by radiation, ΔH_c the change in convective heat loss and K a constant.

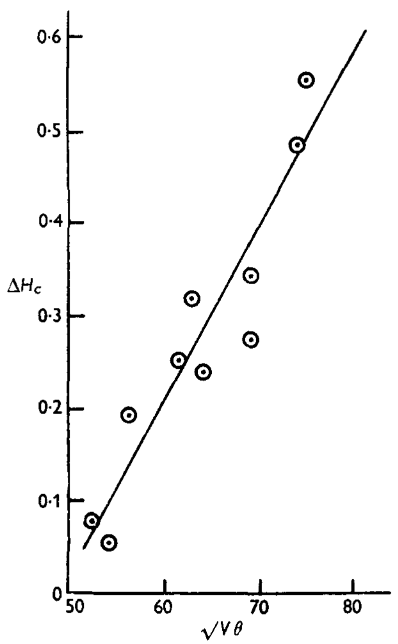

Fig. 6

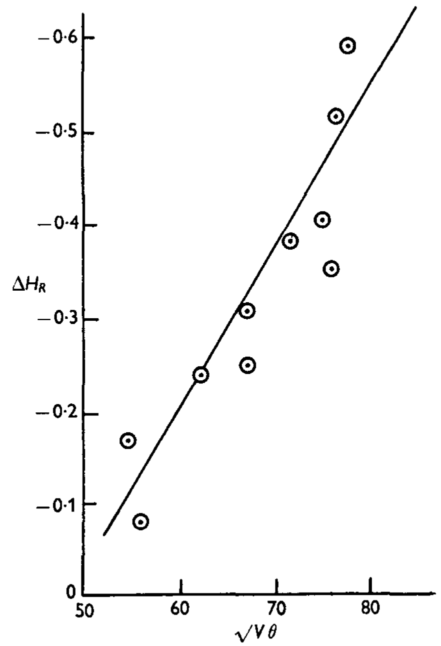

Fig. 7

Fig. 6. Calculated change in convective heat loss ΔH_c (cal./cm.²/sec. × 10^3) against $\sqrt{V\theta}$ (cm./sec., ° C.) for conditions evoking a sensation of warmth.

Fig. 7. Calculated change in radiative heat loss ΔH_R (cal./cm.²/sec. × 10^3) against $\sqrt{V\theta}$ (cm./sec., ° C.) for conditions evoking a sensation of coolness.

It has been shown above (equation (i)) that

$$\Delta H_c = a\sqrt{V\theta} - k.$$

Thus, by substitution for ΔH_c, equation (iii) becomes

$$\Delta H_R = K - (a\sqrt{V\theta} - k), \tag{iv}$$

$$\Delta H_R = K_1 - a\sqrt{V\theta}, \tag{v}$$

where K_1 is another constant, and thus plotting ΔH_R against $\sqrt{V\theta}$ should result in a linear regression curve with a slope of $-a$. Such a regression curve has been plotted in Fig. 7. The value of a is $+0{\cdot}0000175$, which is in remarkable agreement with the convection coefficient of 0·000018 determined from the data for sensations of warmth.

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(5) *Comparison with other coefficients for convective heat loss*

It is of interest to compare the value of 0·000018 for the convection coefficient in equation (ii) with values arrived at by other workers by methods very different from those used here. Nelson, Eichna, Horvath, Shelley & Hatch (1947) determined the heat loss from nude men in a hot environment and, by the method of partitional calorimetry, dissociated the separate effects of radiation, convection and evaporation. The value of their convection coefficient was, in terms of the units used here, 0·00002. Winslow, Gagge & Herrington (1940), working at the John B. Pierce Laboratory, had obtained a convection coefficient of 0·00003, also by the technique of partitional calorimetry. But Nelson and his colleagues point out that these latter observations were made not in a wind tunnel with linear air flow, but in a booth in which the air was stirred up by fans and the movement was extremely turbulent. Thus Nelson and his colleagues explain the difference between the two coefficients, and it would be expected that the results from the present investigation would agree with those from their work rather than with those from the Pierce Laboratory.

This difference between turbulent and fairly laminar air movement may well explain the discrepancy between the expected value of 0·00089 cal./cm.^{2}/sec. for the basic rate of heat loss in the standard environment in the present experiments, and the value of 0·00064 cal./cm.^{2}/sec. obtained by application of the derived equation. The convection coefficient in this equation resulted from experimental exposures to linear air flow normal to the exposed surface. On the other hand, the air movement in the cubicle resulted from the admission of air from above the subject, and thus would be expected to be turbulent in nature with a tendency to move along the exposed surface. Thus any calculation of the rate of convective heat loss in the standard environment should be made with reference to a coefficient for turbulent conditions, which would be greater than the coefficient for linear air flow. The coefficient of Winslow *et al.* for turbulent conditions exceeded by 50 % that of Nelson *et al.* for conditions where the flow was more nearly linear. Applying such a correction to the value of 0·00064 cal./cm.^{2}/sec. given by the constant in equation (ii) for the basic heat loss by convection in the standard environment, we get 0·00096 cal./cm.^{2}/sec., which agrees closely with the value of 0·00089 for the constant k in the equation.

A further check on the validity of the coefficient is provided by a purely physical approach. Eckert (1950) quotes an equation due to Squire for the calculation of the convection coefficient for the heat transfer at a point on a cylinder when the direction of the air flow is normal to the axis. For a cylinder of diameter 0·6 ft., which may be taken as a fair approximation to the head, a convection coefficient of 0·000013 is obtained by this method, which figure is in good agreement with the values of the coefficient found by the physiological approaches.

(6) *Stimulation by radiation and convection*

(*a*) *Warmed moving air*

By application of the convection equation to the data from the warmed moving air experiments it is possible to estimate what increase in air temperature would

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have been necessary to evoke a sensation in the absence of any change in the radiation. Such estimates may be of importance when one is considering the effects of draughts from ventilation inlets. Calculation shows that the sudden imposition of an air stream at velocities of 35, 50, 65, 90 and 100 ft./min. would require that the temperature of that stream should be raised to at least 3·7, 4·9, 6·1, 6·8 and 8·0° C. above room temperature if local sensations of cooling were to be avoided, whereas if the temperature was raised by more than 4·9, 6·9, 7·8, 8·3 and 9·3° C. respectively for the same air speeds, sensations of warmth would be caused.

The above figures are based on the threshold, or 50 % response, values for trained subjects. Rydberg & Norbäck (1949) quoted increments in air temperature necessary to prevent a sensation of coolness in persons seated in an air stream. At the air speeds mentioned above, they found that the increments of temperature necessary were 1·5, 2·0, 2·5, 3·3 and 4·0° C., which are lower than those mentioned in the previous paragraph. They agree more closely with the increments which in the present study would have evoked a response on 95 % of occasions, viz. 2·2, 2·6, 3·8, 4·6 and 5·5° C. However, Rydberg & Norbäck were probably concerned with something more definite and long-lasting than a 'just perceptible' sensation.

(*b*) *Radiation and moving air*

By a similar consideration of the appropriate data, it is possible to estimate what changes in radiation would have been necessary in the absence of any change in air temperature to evoke a sensation of warmth at various air speeds. These changes in radiation intensity, expressed in terms of an increase in the mean radiant temperature, are 2·1, 4·0, 5·6, 7·1 and 7·8° C. at air speeds of 35, 50, 70, 90 and 100 ft./min. On the whole, a change of 1° C. in air temperature is equivalent to 1·4° C. change in mean radiant temperature in its effect upon thermal sensations. From the result of studies of comfort conditions made in factories Bedford (1936) derived the following equation for equivalent temperature:

$$\text{equiv. temp.} = 0{\cdot}478tw + 0{\cdot}522ta - 0{\cdot}0147\sqrt{V}(100 - ta),$$

where tw is the mean radiant temperature in ° F., ta the air temperature in ° F. and V the air speed in ft./min. This equation also indicates that air temperature has a greater influence on comfort than has the mean radiant temperature. With an air speed of 50 ft./min. a change of 1° F. in air temperature has an effect similar to 1·3° F. change in mean radiant temperature, which is in close agreement with the findings from the present investigation.

(7) *Thermal changes in relation to freshness*

Bedford & Warner (1939) found that changes in both the average value and the variability of the air speed and in the temperature had a marked effect upon impressions of freshness. A change in air temperature of 5° F. in the summer, or 3·5° F. in the winter, was sufficient to change the impression of freshness by one unit on their arbitrary scale. Transient fluctuations of air temperature about the mean value appeared to have no significant influence, but they observed only small fluctuations, 73 % of their observations varying by less than $\pm 0{\cdot}4°$ F. With a mean air speed of 40 ft./min. a total variation of 11 ft./min. or ± 14 %, also altered the impression of freshness by one unit.

Taking an air temperature of 20° C. (68° F.) with a mean air speed of 40 ft./min. as representing common indoor conditions, in which the skin temperature on the forehead would be about 33·3° C. (91·9° F.), and applying equation (ii), it can be computed that a change of about 1° C. in the temperature, or of 5 cm./sec. (10 ft./min.) in the air speed would be required to evoke a sensation of warmth.

From an unpublished equation, based on the results of Bedford & Warner, the effect of such changes upon the subjective impressions of freshness can be estimated. A change in the air temperature of the order of 1° C mentioned in the previous paragraph, would change the freshness impressions by $\frac{1}{2}$ unit on the scale used by these workers, and similarly a change in air speed from 40 to 30 ft./min. would result in a change of about $\frac{3}{4}$ unit. Hence it is not surprising that, under the conditions which they encountered, with much smaller fluctuations in air temperature, Bedford & Warner found no evidence of a correlation between the changes in air temperature and impressions of freshness.

Thus changes, particularly in the variability of air movement, which produce only the slightest thermal sensation in trained subjects, changes which would doubtless pass unnoticed if they occurred in normal circumstances, may well be sufficient to have a marked effect upon the freshness and pleasantness of the environment.

SUMMARY

The results of experiments designed to determine the threshold values for various thermal stimuli have been reported. The threshold increments in the intensity of radiation in 'still' air were determined first for several areas of exposure. In further experiments the effects of simultaneous changes in both the speed and temperature of the air, and the air speed and radiation intensity, were examined.

The data from these experiments were then used to estimate the relation between the temperature and speed of the air on the rate of heat loss by convection. The findings were shown to be in good accord with previously published data.

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