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Spontaneous magnitude estimation of thermal discomfort during changes in the ambient temperature*

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SUMMARY

Thermal comfort sensations are often studied in isolation, with the subjects' attention specifically directed towards their evaluation, both by instructions and by the recurrent act of questioning. A closer approach to the field situation, in which room temperature is at most a background stimulus, is made possible by the method of spontaneous magnitude estimation of thermal sensation. Thirty-six male and 36 female 17-year-old subjects in standard cotton uniforms (0·7 clo) were exposed in groups of 4 in a climate chamber to patterns of changing air temperature typical of conditions in occupied classrooms. Temperatures remained within the range 20–29° C. and did not increase more rapidly than 4° C./hr. Each individual recorded his thermal sensation on a dial voting apparatus, registering changes spontaneously as a secondary task while performing mental work during three successive 50 min. periods, with 10 min. breaks between. It was thus possible to obtain a measure of the time course of thermal discomfort sensations, including the extent to which they distracted attention. Significant differences were found between the responses of males and females, males in general feeling hotter and reacting more rapidly to changes in temperature. Response distributions are given in detail.

INTRODUCTION

Questionnaire methods currently in use to obtain measures of thermal comfort tend to decrease the inherent sensitivity of this sensation by using arbitrary category scales. Their reliance on what might be termed 'fixed-interval intrusion' and 'time-integrated retrospection' mean that it is difficult to study how such elusive time-variant factors as attention, arousal and effort may be affecting thermal comfort (Wyon, 1970*a*). Changes in these intervening variables can radically affect the relevance of thermal comfort in a real situation, as when a

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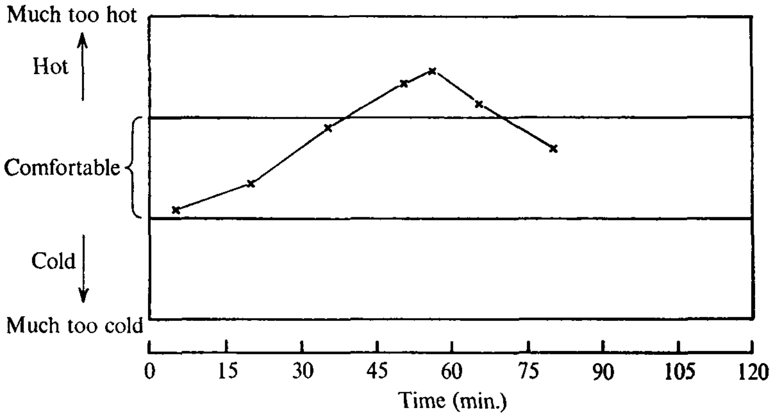

Fig. 1. Chart voting. Each subject has a chart on which he must place a cross whenever he becomes aware of his thermal sensation.

narrowing of the attentional field due to increased arousal or to concentration on performance leads to a marked reduction in the subjective importance of thermal discomfort stimuli. In such cases the intrusive act of questioning about thermal comfort can totally alter the attentional situation. This calls in question the validity of applying conventional questionnaire methods to the study of changes in thermal stress.

It is the purpose of this paper to propose a simple standard method for obtaining measures of thermal comfort and discomfort, a method which has some unique advantages for the study of subjective response to a changing thermal environment. The method is illustrated by its application in a study of such temperature changes as might occur in school classrooms, carried out in a climate chamber with 17-year-old pupils as subjects.

PILOT EXPERIMENT

Chart voting

As part of the development of the method, a preliminary experiment was carried out at the University of Aston in Birmingham (Wyon, 1968, unpublished).

Groups of about 25 17- to 19-year-old British students attending normal mathematics lectures in a lecture theatre with controlled-temperature air supply recorded their thermal discomfort sensation as a function of time on forms of the type shown in Fig. 1.

Their instructions were to place a cross on the chart whenever they became aware of their thermal discomfort sensation in the course of the lecture, taking care to locate it correctly on the time axis (abscissa). The position of the cross on the thermal discomfort sensation axis (ordinate) should indicate their thermal vote at that time on a continuous scale from 'much too cold' to 'much too hot'. There were no objections from the subjects to the idea of a comfort zone occupying one-third full scale. In all, over 120 students took part, each group being exposed to a different rate of rise of temperature. Difficulties in controlling the temperature and temperature differences from front to back of the steeply ramped lecture

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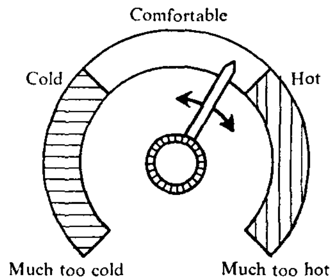

Fig. 2. The dial on the dial vote apparatus is divided in three zones: a cold, a comfortable and a hot zone. The pointer is moved to a new position, whenever the subject becomes aware that his thermal sensation has changed.

theatre made it difficult to discriminate effects of rate of rise *per se*, but it was clear that the subjects could record meaningful estimates of thermal discomfort sensation in this way, and that they responded to changes of less than 1° C. in air temperature.

When experiments must be carried out on large groups of subjects, it is justifiable on practical grounds to complicate their task by giving them the responsibility of recording time, but it does introduce a source of error as well as adding to their work load. Experiments on individuals or small groups can with advantage be carried out using the 'dial vote' version described in the following section.

METHOD

Dial voting

Each subject was provided with a dial as shown in Fig. 2. It resembled a thermostat control, with the range of adjustment covering a 270° angle, divided clearly into three equal zones, each 90°. The central zone was green, and marked 'comfortable', the zone to the left of centre was blue and marked 'cold', and the zone to the right of centre was red and marked 'hot'. A pointer could be set to remain at any point on the scale, whose extremes were marked 'much too cold' and 'much too hot' as shown. No other graduation or wording appeared on the scale. Subjects were instructed to ensure that the deviation of the pointer from the centre of the scale always represented the magnitude of their thermal discomfort sensation, and it was pointed out to them that this implied that they should alter the setting whenever they became aware that their thermal discomfort sensation had changed. It was emphasized that they would not be reminded to make these adjustments during the experiment, and must remember to do so themselves. They were not given any idea of whether the temperature would go up or down or remain constant; indeed, if they asked, it was emphasized that they did not know and should therefore record their sensation rather than their expectation. The dial faces were recessed so that each subject could only see his own dial setting. Subjects were told that the end-points of the scale represented unbearable extremes, where they would be obliged to leave the climate chamber, and that such extremes would not occur in the experiment. This instruction was intended to discourage subjects

Table 1. *Physical characteristics of subjects*

Group	No.	Age (years)	Height (cm.)	Weight (kg.)	Du Bois area (m.^{2})	Skin-fold thickness (mm.)
Males	36	16·6 ± 0·9 (15–18)	179·0 ± 5·0 (169–191)	64·9 ± 7·0 (54–79)	1·81 ± 0·11 (1·63–2·00)	70·2 ± 18·7 (47–108)
Females	36	16·4 ± 0·7 (15–18)	162·2 ± 5·9 (151–180)	53·9 ± 4·9 (45–64)	1·56 ± 0·08 (1·42–1·81)	90·4 ± 18·8 (68–154)

Mean values ± 1 standard deviation. Ranges in parentheses. Skin-fold thickness is the sum of measurements at five sites for each subject: mid-axillary, supra-iliac, abdominal, triceps and thigh.

from making settings at or close to the end-points, thus avoiding compression of scale. The results suggest that this aim was achieved, as the scale was linearly related both to temperature and to the Bedford scale.

By connecting each pointer to a potentiometer in a simple bridge circuit the setting on each dial was remotely and continuously recorded in such a way that readings were available every 72 sec. with an accuracy of 1 % of full scale. It was ensured that settings in the three zones actually gave values of 0–33, 34–66, 67–100 respectively, so that transitions between comfort and discomfort were accurately recorded. The scale was linear with respect to dial setting.

Experiment

The subjects were 72 healthy Danish high-school pupils of high ability; they were volunteers, but paid by the hour; each subject attended only once. None of them were acclimatized to heat. The physical characteristics of the male and female groups, each of 36 subjects, are given in Table 1.

Denmark has a temperate Atlantic climate, and during the experimental period from 17 September to 10 October 1969 the local average maximum and minimum outdoor temperatures were 15·1° C. (range 10–21° C.) and 8·9° C. (range 2–14° C.) respectively. The experimental period was preceded by stable outdoor conditions at a slightly higher temperature level.

Three different temperature conditions were used in the climate chamber exposures. The control condition (condition 0 in Fig. 4) was a saw-tooth variation of temperature, rising from 20 to 23° C. in the course of 50 min., then decreasing to 20° C. in the rest period of 10 min. This temperature variation was repeated twice during the next 2 hr. In condition 1 (see Fig. 4) a base-line increase of 1° C. per hour was imposed on the saw-tooth variation of condition 0, with the result that the temperature rose 4° C. in 50 min. and fell 3° C. in the next 10 min., starting as for condition 0 at 20° C. and thus ending at 26° C. after 3 hr. In condition 2 the same variation occurred but at a higher level; the temperature was initially 23° C. and thus became 29° C. after 3 hr. (see Fig. 4).

The temperature was measured as the arithmetic mean of air temperature and radiation temperature and will in the following be referred to as temperature only. The chamber was especially designed for dynamic studies, and the walls inside the insulation have a very low thermal capacity. The absolute humidity of the air was constant at 9 mm. Hg (corresponding to 50 % R.H. at 20° C.), the air velocity was 12 ± 3 cm./sec. and the air supply rate was 600 m.^{3}/hr.; there was no recirculation. Further data on the performance of the climate chamber are given by Andersen & Lundqvist (1970).

Procedure

The subjects attended school as usual during the first 3 hr. of the day; after lunch each day single-sex groups of four were taken by car to the climate laboratory, where they changed into standard cotton-drill suits (Plate 1). Cotton shorts and a cotton T-shirt were worn underneath, together with cotton socks and light canvas shoes. The total insulation value of this ensemble was 0·7 clo. As the suits are very similar to the denim jeans and jackets that are frequently worn in school by Danish pupils of this age, both male and female, they can be considered a fairly typical 'basic school clothing'. In practice, there will be more deviations towards higher insulation values, as when a woollen sweater is worn, than towards lower insulation. As the present experiment was intended to derive recommended maximum values for classroom temperatures, it would have been inappropriate to take account of the effect of extra items of clothing. It is both cheaper and more effective to insist that such extra items be removed than to ensure that classroom temperatures should be lowered on their account. On entering the climate chamber, subjects were seated at individual desks facing a fifth desk used by one of the experimenters (DPW), who was present throughout the total exposure period. The subjects worked continuously at a programme of psychological tests (the results of which will be presented in a forthcoming paper) and only in the rest periods were they allowed to relax and walk around in the chamber. Skin and rectal temperatures were recorded continuously and ECG records were taken at intervals. These and other physiological observations will be the subject of a further article.

The subjects were instructed in the use of the dial voting equipment as set out above. They were reminded at the start of each 50 min. period that they should adjust the setting spontaneously, but during each such period no mention of dial voting was made. At the beginning and end of each period, while still sitting at their desks in the climate chamber, the subjects also voted on the seven-category Bedford scale (Bedford, 1964).

RESULTS

Relation between Bedford scale and dial vote

Mean thermal votes obtained on the Bedford thermal voting scale at the beginning and end of each 50 min. period are shown in Fig. 3 for males and females separately. Conventional questionnaire voting was limited to these two occasions to interfere as little as possible with the spontaneous thermal votes. The temperature variations (Fig. 4, lower section) are clearly reflected in the variation of the mean thermal votes (Fig. 3), and also in that of the mean dial votes (Fig. 4). It was noticed that individuals often adjusted their dial vote setting by as little as 1 %

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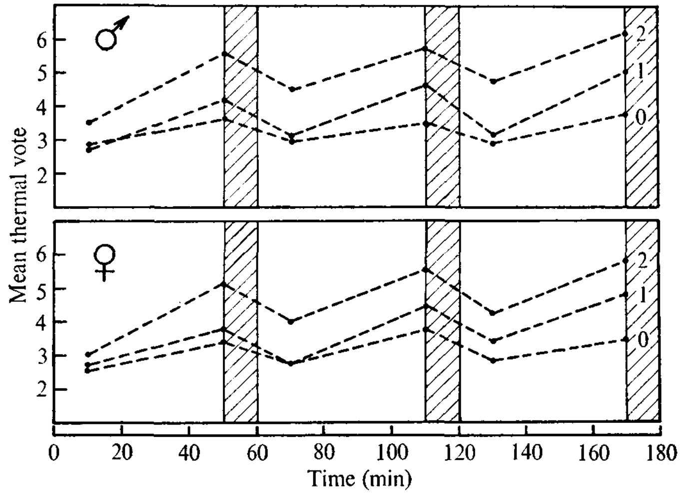

Fig. 3. The mean thermal votes on the seven-point Bedford scale obtained at the beginning and end of each hour of the three experimental conditions 0, 1 and 2. On this scale 4 is the centre (ideal comfort), 1 and 7 much too cold and much too hot respectively and 2 and 6 too cold and too hot respectively. The hatched columns represent rest periods with a 3° C. decrease in temperature.

full scale, i.e. they used the possibility of making much finer discriminations than are possible with the Bedford seven-category scale. A comparison has been made between the thermal votes recorded by each subject at the beginning and end of each period and the simultaneous dial vote setting. These scatter diagrams are shown in Fig. 5(*a*) and (*b*) for males and females respectively, and no systematic deviations from a straight line are apparent. The Pearson correlation coefficient for males is 0·85 and for females 0·84, and the corresponding linear regression equations are $D = 12{\cdot}4B + 4{\cdot}2$ and $D = 11{\cdot}9B + 2{\cdot}7$ respectively (where D is the dial vote and B the Bedford scale vote). The regression lines do not differ significantly in any respect. In addition, no significant differences were found between regression lines drawn separately for votes at the beginning and end of each session, for either sex.

Dial voting therefore appears to result in a measure of thermal comfort fully comparable with the Bedford scale. Since in addition it overcomes the general objections to the use of questionnaire methods that were raised in the introduction, it would appear well suited to the investigation of changing temperatures. Results obtained by means of dial voting are analysed in the following sections.

Analysis of variance of dial votes

Dial vote settings were evaluated at regular intervals of about 5 min. (4 timing units, equal to 4·8 min.) for each person separately throughout his or her exposure. They were expressed as a whole-number percentage of full scale, with 0 and 100 as the extremes of cold and hot discomfort respectively. Thus the comfort zone encompassed 34–66, and 50 represented ideal comfort. Fig. 4 shows how the mean

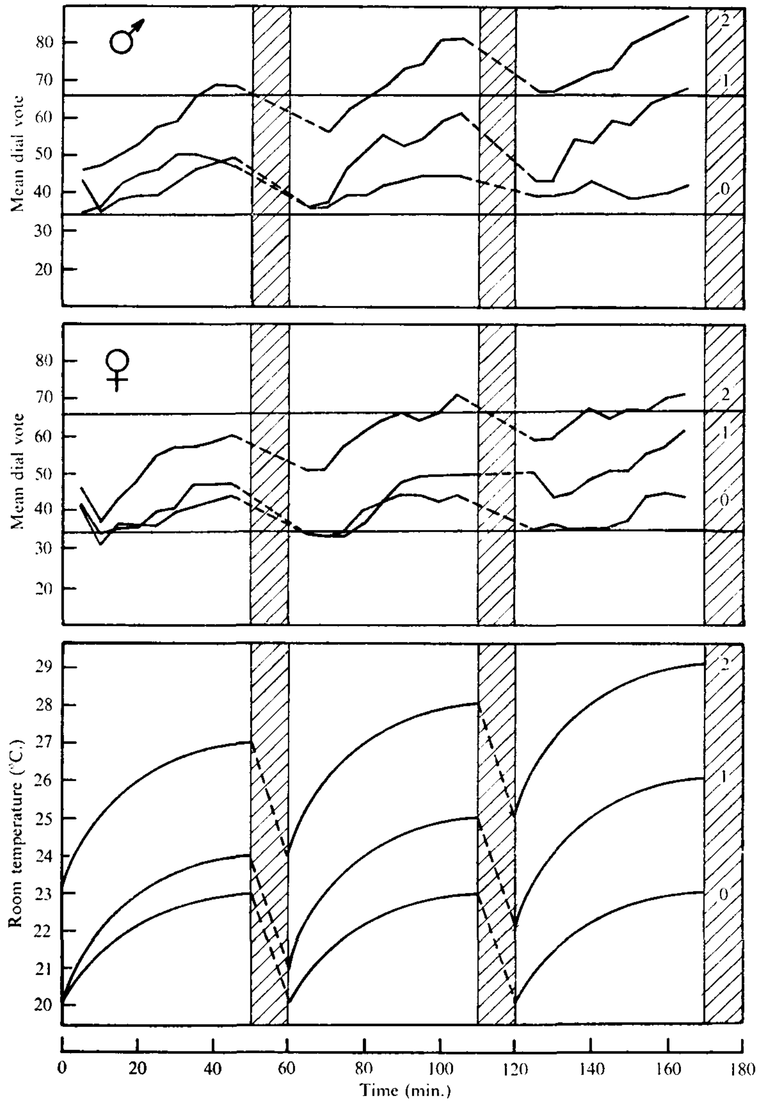

Fig. 4. The two upper sets of curves show the variation with time of the mean dial votes. The boundaries between the cold and the comfortable zone and between the comfortable and the hot zone are shown as horizontal lines at 33 and 67 respectively. The lower set of curves show the variation with time of ambient temperature (surface temperatures = air temperature) during the three experimental conditions 0, 1 and 2. The hatched columns represent the rest periods.

setting for groups of 12 boys or girls changed with time over their three 1 hr. exposure periods, for each of the three temperature conditions.

In order to examine the significance of such differences as are apparent in the figure, analysis of variance was carried out with dial vote setting as dependent variable, for each temperature condition separately. Time and temperature effects are confounded throughout, as must be the case in any investigation in which subjects are exposed to temperatures that change during rather than between

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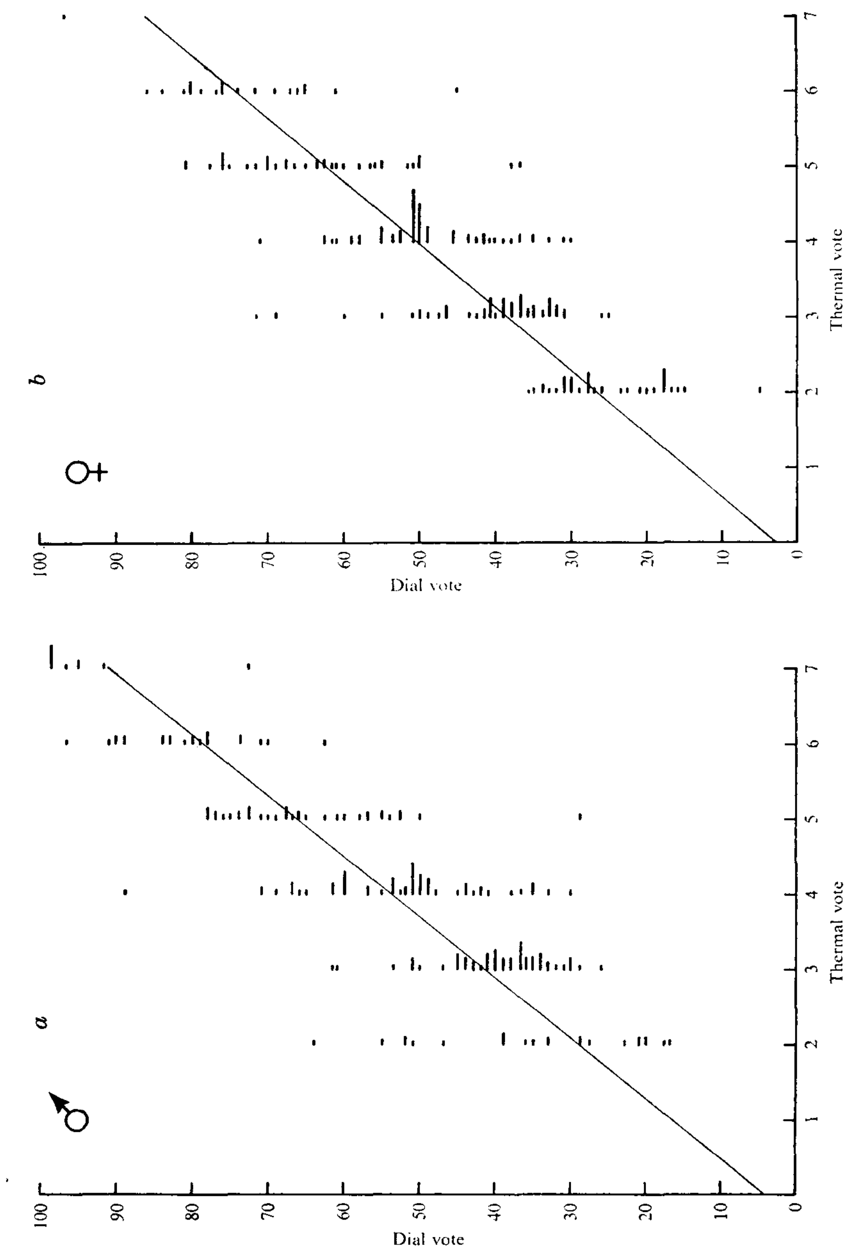

Fig. 5. The distribution of dial votes obtained simultaneously for each category of thermal vote for males and females separately. The shortest lines represent one subject, longer lines a proportionally greater number of subjects.

Table 2. *Dial vote: analysis of variance summary table for conditions* 0, 1, 2

(The analysis examines the effects of the three independent factors Sex, Periods and Minutes, taking dial vote as the dependent variable. Within a given temperature condition, each subject was present for three successive periods, each of 50 min. The analysis of variance takes account of the fact that the dependent variable was recorded repeatedly from the same subject in successive minutes and periods by deriving error terms that include the interaction, if any, between subjects and the relevant factor. (See Winer (1962), pp. 319–35.)

		Condition					
		0		1		2	
Source of variation	D.F.	MS	F	MS	F	MS	F
Between subjects							
Sex	1	751·86	< 1	5,910·26	4·49*	10,771·86	7·55*
Subjects within	22	1,543·86	—	1,317·59	—	1,426·43	—
Within subjects							
Periods	2	183·38	< 1	6,852·37	11·31***	14,450·04	26·46***
Sex × periods	2	38·45	< 1	337·86	< 1	420·15	< 1
Periods × subjects within groups	44	459·18	—	605·84	—	546·07	—
Minutes	8	720·33	9·74***	3,177·06	26·66***	3,803·83	44·42***
Sex × minutes	8	36·30	< 1	357·22	3·0**	193·94	2·26*
Minutes × subjects within groups	176	73·97	—	119·17	—	85·64	—
Periods × minutes	16	104·38	1·95*	103·16	1·25 NS	78·06	< 1
Sex × periods × minutes	16	69·26	1·30 NS	70·83	< 1	45·34	< 1
Periods × minutes × subjects within groups	352	53·42	—	82·28	—	86·47	—

NS Not significant. * Significant at 0·05 level. ** Significant at 0·01 level. *** Significant at 0·001 level.

successive exposures. As temperatures changed non-linearly with time it was decided to take time as the independent variable for the purpose of analysis. The factors investigated were Sex (2 levels), Periods (3 levels, for the three successive hours of exposure) and Minutes (9 levels, roughly 5 min. intervals, covering the first 40 min. of each exposure period). The final 10 min. of each period were disregarded, partly because Bedford scale voting took place towards the end, which could have affected dial vote settings, and partly because there was a certain amount of variation in the exact time at which chamber temperatures began to decrease at the end of each period. The statistical model for the analysis of variance was that of a three-factor experiment with repeated measures on the last two factors (Periods, Minutes). A full exposition of this model is given on pages 319–35 of Winer (1962). The total of 36 boys and 36 girls had been assigned at random to the three temperature conditions, so 12 boys and 12 girls experienced each condition.

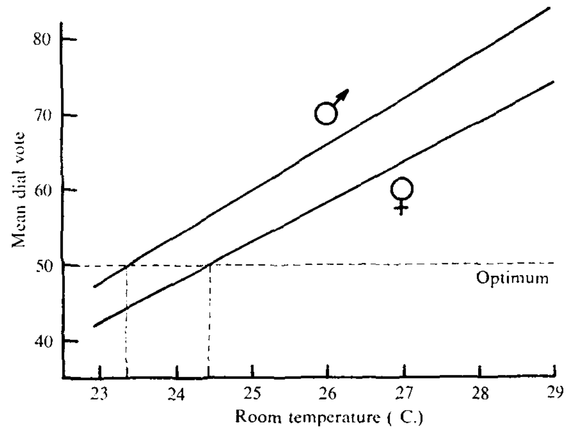

Fig. 6. Relation between temperature and mean dial vote for males and females separately.

Temperature condition 0 (20–23, 20–23, 20–23° C.)

Table 2 sets out the analysis of variance of dial votes in condition 0. There were no significant main effects of sex, and no interactions with the sex factor. There were no differences between periods, and here it should be remembered that there was in fact no base-line change in condition 0 – the temperature rose from 20 to 23° C. in all three periods. However, the main effect of time within each period ('Minutes') was significant ($P < 0{\cdot}01$), showing that subjects responded to the 3° C. temperature change even though most of the dial votes were within the comfort zone. There was a significant interaction between Periods and Minutes ($P < 0{\cdot}05$). An examination of Fig. 4 shows that dial votes tended to increase by a progressively smaller amount in the later periods.

Temperature conditions 1 (20–24, 21–25, 22–26° C.) *and* 2 (23–27, 24–28, 25–29° C.)

Table 2 sets out the analysis of variance of dial votes in conditions 1 and 2. The results are identical in each condition. The main effect of Sex was significant ($P < 0{\cdot}05$); boys felt significantly hotter than girls. The main effect of Periods was significant ($P < 0{\cdot}001$), and there was no interaction with Sex; boys and girls detected the base-line temperature rise of 1° C./hr. The main effect of Minutes was significant ($P < 0{\cdot}001$), and there was a significant interaction with Sex ($P < 0{\cdot}05$), though not with Periods. Subjects detected the temperature rise of 4° C. within each period, and the rate of increase of dial vote with temperature was the same in each period in spite of the base-line temperature rise. Boys tended to alter their dial vote settings by a greater amount than girls in response to a given temperature change.

Relation between dial vote and temperature

Correlation between mean dial vote and temperature

Values of the mean dial vote for each group of 4 subjects at 10, 30 and 50 min. from the start of each period have been used to calculate the regression lines shown

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in Fig. 6. Boys and girls are shown separately. The scatter diagrams indicated a linear relationship in each case. It can be seen that girls tended to prefer a slightly higher temperature than boys, and there is a clear indication that girls increased their dial vote more slowly with temperature than boys. These points have been examined by means of analysis of variance and were shown to be significant. The correlation coefficients tended to increase towards the end of each hour, reaching 0·65 and 0·67 after 50 min. for boys and girls respectively. Optimum temperature for boys was 23·4° C. (dial vote 50) and the regression line remained in the comfort zone over a range of 5·5° C. (20·6–26·1° C.). Optimum temperature for girls was 24·4° C. and the regression line remained in the comfort zone over a range of 6·4° C. (21·2–27·6° C.). At the limits of these ranges, however, 50% of subjects would be uncomfortable, and a much narrower range of temperatures would be necessary to ensure that all subjects remained within their individual comfort zones. The following subsection deals with this point.

Comfort and discomfort distributions against temperature

By examination of the dial vote settings maintained by each individual at 10, 30 and 50 min. from the start of each hour, the proportions too cold, comfortable and too hot were obtained and related to the measured air temperature. Probit analysis was performed (Finney, 1947), yielding the calculated regression lines shown in Fig. 7. They show for each sex separately the expected proportions too hot and too cold at each temperature (left-hand probit scale). By subtraction, the proportion comfortable may be obtained; such distribution curves are shown in Fig. 7 for each sex separately (right-hand percentage scale). This presentation of comfort and discomfort distributions was suggested by Wyon, Lidwell & Williams (1968).

Where the probit regression lines intersect, the proportion too cold is equal to the proportion too hot. Any deviation from this point results in an overall increase in the total proportion uncomfortable. For boys, the lines intersect at 23·8° C.; for girls, at 25·0° C. However, for a mixed population the 'optimum' temperature is where the proportion of girls too cold is equal to the proportion of boys too hot. This point occurs in the present data at 24·3° C., at which temperature 16% of girls were too cold and 16% of boys were too hot. In determining the optimum temperature for any population it should be remembered that those too cold can always wear more clothing, whereas there is usually a limit to how much clothing those too hot can remove. The limiting factor in deciding classroom temperatures should perhaps be the expected proportion of boys who are still too hot when wearing a reasonable minimum of clothing. In the present experiment the clothing insulation (0·7 clo) was probably close to that of the usual clothing worn in schools by pupils of this age. On the other hand the activity level during the experiment was almost certainly lower than in normal school conditions owing to the lack of active recreation between periods, and the air velocity was somewhat higher than is common in school classrooms (Andersen & Lundqvist, 1966). Both of these factors will tend to reduce the temperatures required for comfort in practice. Where conditions do correspond to those of the experiment, a maximum tempera-

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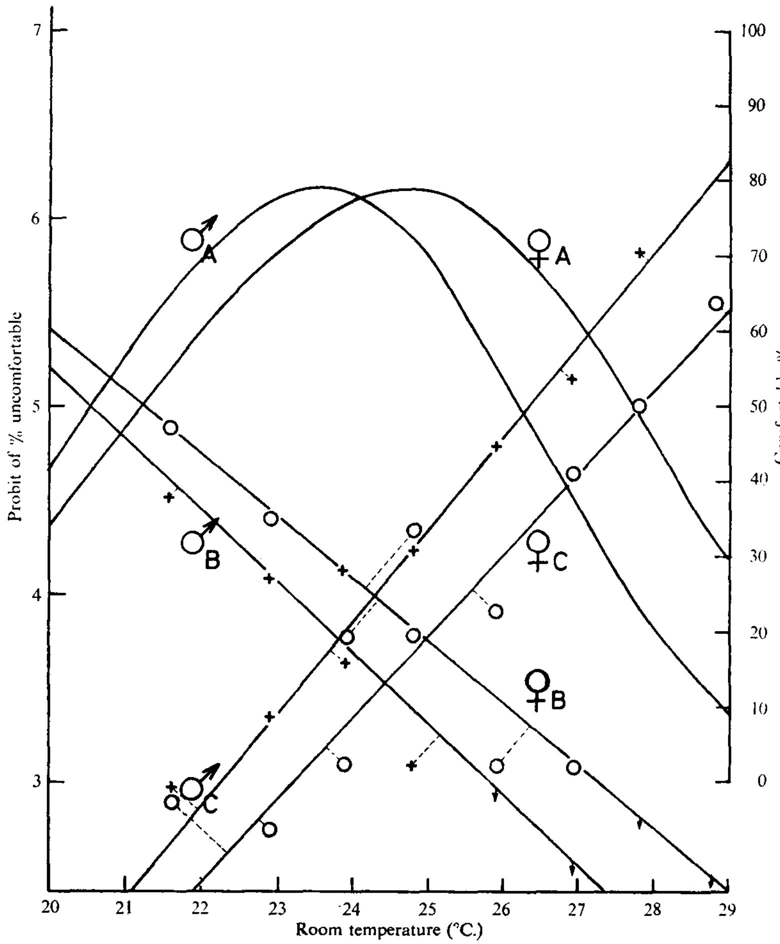

Fig. 7. Proportion of subjects comfortable, uncomfortably cold and uncomfortably hot at various temperatures. Males and females are shown separately. The two curves A show the percentage comfortable (right-hand scale). The two lines B show the probit of the percentage uncomfortably cold and the two lines C show similarly the uncomfortably hot (left-hand scale).

ture between 23 and 24° C. would seem reasonable (Fig. 7), for at 23·7° C. 10 % of boys were too hot (and 20 % of girls were too cold) and at 23·0° C. 5 % of boys were too hot (and 28 % of girls were too cold).

Comfort/discomfort dichotomy from dial vote-temporal effects

There is a quite explicit dichotomy between dial vote settings that are in the comfort zone and settings that are outside it. Using only this dichotomy, and thus avoiding any assumptions about scaling, it is possible to follow the time course of subjective response to imposed temperature changes. Two measures were derived to characterize a subject's response to the temperature change within a given 50 min. period: the number of minutes that elapsed before he first spontaneously made a dial vote setting in the 'too hot' zone, and the total number of minutes for which dial vote settings were maintained in the 'too hot' zone. The former

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Table 3. *Mean number of minutes tolerated before vote of 'too hot' was recorded* (12 *subjects of each sex encountered each condition*)

	Boys			Girls		
Period ...	1	2	3	1	2	3
Temperature condition						
2	33·5	12·8	10·6	35·6	24·0	12·7
1	45·6	34·7	28·8	44·2	45·9	33·0
0	43·3	50·0	50·0	41·7	48·5	50·0

measure is applicable only to rising temperatures, while the latter is quite generally applicable to any pattern of rising and falling temperature. Both measures make use of the spontaneous nature of dial vote responses. Non-parametric statistics were used in the analysis (Siegel, 1956).

Table 3 shows the number of minutes for which dial vote settings remained within or below the comfort zone, averaged over 12 subjects of each sex, for each period of each temperature condition. It may be seen that (*a*) there was a tendency for subjects to become 'too hot' sooner in the warmer conditions, (*b*) boys tended to become 'too hot' sooner than girls, and (*c*) the base-line rise of 1° C. per hour during conditions 1 and 2 was reflected in the results. The significance of these effects was tested both for the criterion of 'minutes tolerated before vote of "too hot" recorded' and for the more general criterion of 'total minutes for which vote of "too hot" recorded', using the same procedures.

Kruskal-Wallis analysis was used to test the extent to which each criterion distinguished between temperature conditions. Values of ($P < 0{\cdot}001$) were obtained for each criterion, for boys and for girls separately. Clearly both sexes became 'too hot' sooner in the warmer conditions, and were uncomfortably hot for a greater proportion of each exposure.

The Mann–Whitney U-test was used to test differences between the responses obtained from each sex. No significant difference could be shown on the first criterion within any of the three conditions, but on the second criterion values of ($P < 0{\cdot}01$, $< 0{\cdot}05$, $\geqslant 0{\cdot}05$) were obtained within conditions 2, 1 and 0 respectively. Boys were 'too hot' for a significantly longer time than girls in the warmer conditions. Very few became 'too hot' in the control condition, rendering both criteria insensitive.

Friedman two-way analysis of variance was used to test whether subjects had detected the base-line rise between periods within each temperature condition. On the first criterion, a significant result ($P < 0{\cdot}01$) was obtained for condition 2 only, for each sex separately. On the second criterion, values of ($P < 0{\cdot}01$) were obtained for boys meeting condition 2 and condition 1, whereas a significant value ($P < 0{\cdot}05$) was obtained for girls only in condition 2. It should be remembered that there was no base-line rise between periods in the control condition 0. In condition 2 the base-line rise of 1° C./hr. caused both sexes to become 'too hot' sooner, and to remain 'too hot' for a longer time. In condition 1 the base-line rise caused boys to remain 'too hot' for a longer time.

Table 4. *Adjustments to dial vote in each condition* (12 boys + 12 *girls met each condition, total* 72 *subjects*)

Temp. condition ...		0	1	2
Total no. adjustments in 3 hr. (for each subject)	Boys	3, 3, 4, 6 6, 6, 7, 10 10, 11, 11, 17	2, 3, 7, 10 10, 13, 15, 19 20, 21, 23, 24	6, 8, 9, 10 10, 13, 15, 17 17, 17, 19, 24
	Girls	5, 6, 6, 8 10, 10, 11, 11 13, 17, 18, 18	5, 6, 6, 7 8, 8, 9, 9 9, 10, 10, 14	4, 5, 7, 8 11, 12, 15, 15 18, 18, 19, 20
Mean no. adjustments per person per hour	Boys	2·6	4·6	4·6
	Girls	3·7	2·8	4·2
Mean % time uncomfortable	Boys	21·7 %	33·5 %	59·8 %
	Girls	32·8 %	31·7 %	44·4 %

Discomfort as distraction

Subjects adjusted their dial vote whenever they became aware of their thermal sensation. The frequency with which they did so is thus a measure of the distracting nature of their sensations of thermal discomfort. Only if subjects vote spontaneously can this empirical information be obtained. Any form of elicited response, and particularly fixed-interval questioning, alters the attentional status of thermal sensations.

It seems reasonable that uncomfortable sensations should be more distracting than comfortable sensations. Alternatively, sensations which for some reason distract the subject's attention seem likely to be judged more uncomfortable than sensations which do not. In both cases it may be predicted that subjects voting in the uncomfortable region of the dial vote scale will be more aware of their thermal sensations and will therefore make more frequent adjustments to their dial vote settings. This prediction can be tested in two ways on the present material, as set out below.

Number of adjustments to dial vote in each hour

Table 4 sets out the total number of adjustments made by each subject in the course of his or her 3 hr. exposure, classified according to sex and the temperature condition encountered, and the mean number of adjustments per person per hour for each such group of 12 subjects. In order to decide empirically which temperature conditions were more uncomfortable, the proportion of the total exposure time for which each subject had maintained a dial vote setting of 'uncomfortable' (too hot or too cold) was calculated. Table 4 sets out the mean values obtained in this way for the groups of 12 subjects. It can be seen that for boys, condition 2 was more uncomfortable than condition 1, and condition 1 was more uncomfortable than condition 0. The prediction is therefore that boys would make the greatest number of adjustments to dial vote in condition 2, and the least number in

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condition 0. For girls, condition 0 tended to be slightly too cold, so that condition 1 was the most comfortable and condition 2 the least comfortable. The prediction is therefore that girls could make the greatest number of adjustments to dial vote in condition 2, and the least number in condition 1. The data of Table 4 support these predictions. They may be tested on the individual adjustment data by means of the powerful distribution-free test against ordered alternatives due to Jonckheere (1954). This is a K-sample test of which the two-sample Mann–Whitney U-test used earlier is a special case. Without correction for ties, i.e. at a conservative estimate, the test yields ($P < 0{\cdot}05$) for each sex separately. Evidently subjects did tend to adjust their dial vote setting more frequently under the conditions that caused them to be uncomfortable for a greater proportion of the time.

Mean number of minutes for which each setting was maintained

If subjects adjust their dial vote setting more frequently, the time for which they maintain each setting must decrease on average. The prediction that the average time-lapse between setting will be less when settings are outside the comfort zone than when they are inside the comfort zone may be tested on the present data. If supported, it implies that subjects who are comfortable have longer periods in which they are not sufficiently distracted by their thermal sensation even to alter their dial vote setting. Forty-six of the 48 subjects who encountered condition 1 or condition 2 were both comfortable and uncomfortable at some time during their exposure. For each of these subjects a figure was derived for the length of time each setting had been maintained. Settings were divided into those in the comfort zone and those outside it, and for each subject the time-values linked to each category of settings were averaged and compared by means of the binomial test. One boy had exactly the same average time for settings inside and outside the comfort zone, but 18 out of the remaining 23 boys had longer average times for settings inside the comfort zone. This is significant at the ($P < 0{\cdot}005$) level for a 1-tail test. Thirteen out of 22 girls had longer average times for settings inside the comfort zone, and 9 the reverse. This result does not approach significance. The prediction is thus confirmed at the 0·005 level for boys, but is not confirmed for girls.

Since the pattern of rising temperature usually led to more votes of heat discomfort being recorded later in the exposure, a tendency to alter settings more frequently later in the exposure could have given rise to the above result. The existence of such a time effect was therefore tested on the control group of 24 subjects who encountered condition 0, in which there was no base-line temperature rise. Only settings in the comfort zone were considered. Friedman two-way analysis of variance was used and yielded values that did not approach significance for either sex tested separately. The existence of a time effect on voting frequency can therefore be ruled out with some confidence.

In order to obtain some appreciation of the actual frequency with which subjects adjusted their dial votes, mean setting times were calculated. The 12 boys who encountered condition 0 had a mean setting time in the comfort zone of 15·3 min., whereas the 24 boys who encountered condition 1 or condition 2 had a mean setting time of 13·0 min. in the comfort zone and 10·9 min. outside it. For girls, the corresponding figures are 12·0, 12·7 and 12·7 min. respectively.

DISCUSSION

Temperature conditions

The present study was intended as a laboratory investigation of realistic field conditions. The choice of temperature conditions was based on field measurements in Scandinavian schools (Andersen & Lundqvist, 1966; Andersen, 1970; Erikson & Mandorff, 1967; Antoni, 1969). The constant temperatures which have traditionally been studied for their effects on thermal comfort were seldom found in practice. The typical pattern is one of rising temperature during occupation followed by a rapid decrease of temperature in the interval between lessons when windows may be opened for airing. The temperature range investigated (20–29° C.) is typical for modern school buildings in hot weather; condition 0 for buildings of high thermal capacity and conditions 1 and 2 for buildings of lighter construction with larger windows (Mandorff, 1971). The higher temperatures studied may be critical for the performance of school work. Wyon (1969) found a deterioration in the mental performance of children at 27° C. in comparison with 20 and 23·5° C., and Holmberg & Wyon (1969) found that 27 and 30° C. caused considerable deterioration in school performance in comparison with 20° C. In the present experiment subjects performed a program of tests throughout their exposure. They were thus in a work situation very similar to that in schools, and their simultaneous evaluation of thermal comfort is likely to be the more valid for this reason. However, it should be noted that temperatures judged to be comfortable are not necessarily ideal for the performance of all types of mental work (Wyon, 1970*a*, *b*).

Subjects

The subjects in the present experiment were a random sample of Danish high-school pupils. Comparison of the physical characteristics of the male subjects with published statistics for conscripts in Denmark (Statistisk Årbog, 1969) indicated that they were a typical group. Naturally, no such comparison is possible for the female subjects. However, for both sexes comparisons may be made with the data of Diem (1962) on young Americans of Western European descent. The female subjects of the present experiment did not differ from the American data, whereas the male subjects were both taller and heavier than the American average. The results of the present study are perhaps more valid for Danish schools than are corresponding American studies.

Bedford scale

The comparisons between Bedford scale results and dial vote results indicate that no systematic differences arise. As Bedford scale voting took place only at the beginning and end of each period, the spontaneous dial voting provides more data and has been used for calculations in the present work. However, the Bedford scale results depicted in Fig. 3 provide a means of relating the present results directly to previously published work on constant temperature conditions.

Dial voting

The method of spontaneous dial voting has been shown to be suitable for the study of situations where it is important not to intrude on the attention of subjects. This is the case when subjects are working or are exposed to dynamic temperature conditions, and in almost any imaginable field situation. The analysis of variance shows that the response obtained by the method of dial voting is very sensitive to small temperature changes over long periods (1° C./hr.) and to more rapid changes (4° C./hr.). Significant changes were detected even when the average response was in the comfort zone, which should therefore be regarded not as a neutral zone but rather as a zone of tolerance whose extent may very well be affected by non-thermal factors.

Sex differences

The analysis of variance revealed also significant differences between the response of males and females to changing temperatures. Male subjects in general felt hotter than female subjects at the higher temperatures, and their response increased more rapidly with temperature. The conclusion of Fanger (1970), that there is no difference between males and females in terms of thermal comfort temperatures, was reached on the basis of a literature survey and a number of experiments, all with constant temperatures close to optimal comfort and subjects who were not performing mental work. The conditions under which the present experiment was performed were therefore considerably closer to those of normal school work. It has been pointed out by Fox *et al.* (1969) that there is a physiological sex difference in the functioning of the thermoregulatory system, and the present results are in agreement with the conclusions of these authors, which were that the greatest sex differences would be found under fluctuating temperature conditions. Stolwijk (1969) has reported that men exposed to a sudden change in ambient temperature, from 30 to 50° C., tended to report discomfort earlier and to make higher estimates of the magnitude of their sensation of discomfort than did women. The present results show that this finding is true also for clothed subjects and for moderate rates of change of temperature close to the optimum. The practical consequences and the magnitude of the effect have been discussed in detail and are apparent in Fig. 7. When classes contain boys the temperatures should probably be at least 1° C. lower, and lower still if they are clothed more warmly than the girls.

Some new aspects of the thermal comfort response

Responses obtained by the method of dial voting used in the present experiment may be unambiguously divided into the three categories – too cold, comfortable and too hot – avoiding the controversy over the wording of category scales. The method of probit analysis can thus be more confidently employed, leading to the practically useful distributions of Fig. 7. The fact that dial vote responses are *spontaneous* increases their validity and allows non-thermal factors such as the passage of time to play their part in determining responses. The temporal results provide a new basis for deciding whether a given temperature variation is acceptable; the limiting factor can be the length of time for which subjects are comfortable rather than some arbitrarily scaled estimate of how uncomfortable they become. Conventional questionnaire methods must intrude at given points in time, which in itself is likely to influence the response obtained and reduce the validity of the conclusions.

The fact that responses were spontaneous also made it possible to examine how often subjects were aware of their thermal sensations. This information cannot be obtained by questionnaire methods other than by subjective retrospection, for subjects respond only when questioned. The statistical calculations show that subjects did in fact respond more often when uncomfortable than when comfortable, providing support for the view that thermal discomfort is a distraction and can lead to deterioration of mental performance by distracting attention as well as by altering levels of arousal and effort (Wyon, 1970*a*).

CONCLUSIONS

The present study can be said to have established that spontaneous dial voting is a valid and useful method of obtaining subjective thermal responses, corresponding to conventional methods of obtaining responses and having several useful advantages over them; that thermal discomfort has a distracting effect during mental work; that 17-year-old male and female subjects respond differently to dynamic changes in thermal stress, males in general tending to feel hotter and reacting more rapidly; and that temperatures should not exceed 23° C., even for a few minutes, if no more than 5% of normally clothed boys are to be too hot while performing mental work.

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REFERENCES

Andersen, I. (1970). Medical-hygienic evaluation of indoor climate. *World Meteorological Organization*, no. 225, pp. 159–169.

Andersen, I. & Lundqvist, G. R. (1966). Indendørsklima i skoler (Indoor climate in schools). *Danish State Building Research Institute*, no. 57, 100 pp. Copenhagen: Danish Technical Press.

Andersen, I. & Lundqvist, G. R. (1970). Design and performance of an environmental chamber at the University of Aarhus, Denmark. *International Journal of Biometeorology* **14**, 402–5.

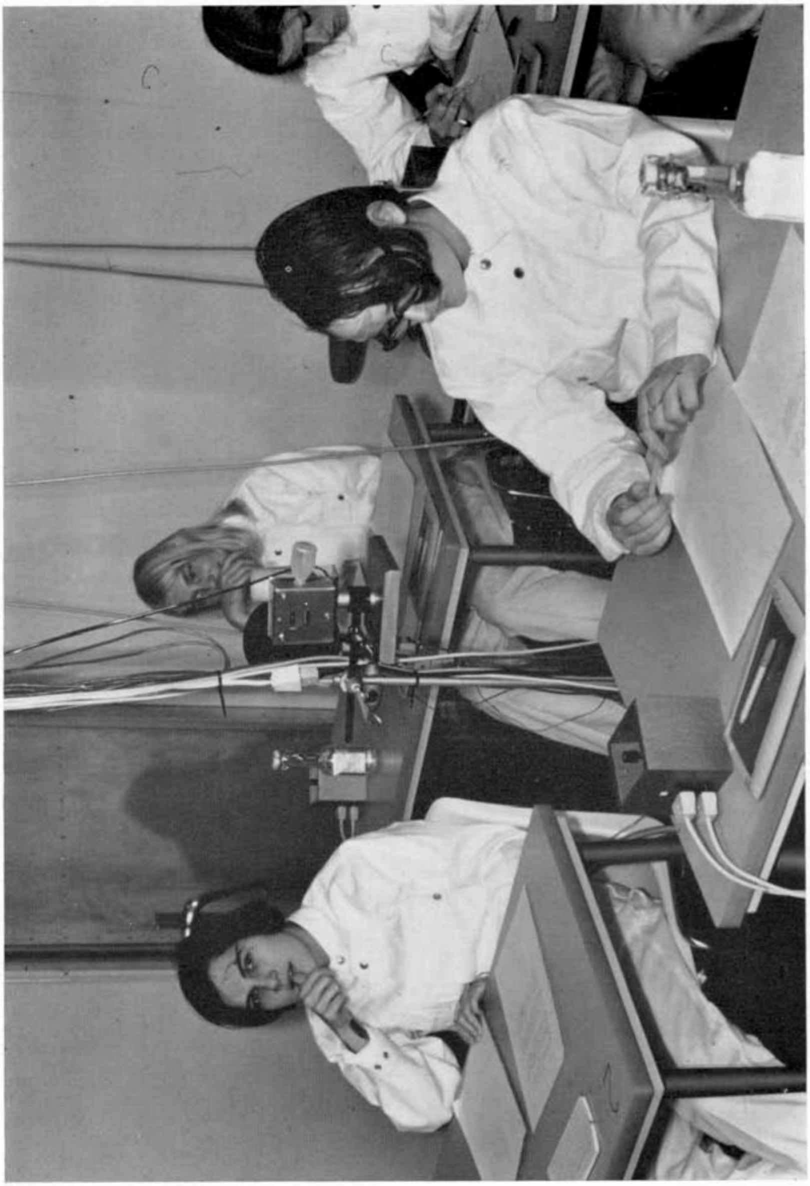
Antoni, N. (1969). Projekteringsunderlag för skolbyggnader för grundskolan [A design study of school buildings]. *National Swedish Institute for Building Research*, no. R 50/69, 17 booklets. Stockholm: AB Svensk Byggtjänst.

Bedford, T. (1964). *Basic Principles of Ventilation and Heating*. 2nd ed. London: H. K. Lewis and Co. Ltd.

Diem, K., ed. (1962). *Scientific Tables*. Basel: J. R. Geigy S.A.

Erikson, B. E. & Mandorff, S. (1967). Lärare bedömer klassrumsklimatet [Teachers' opinions of classroom climate]. *National Swedish Institute for Building Research*, no. R 31/67, 52 pp.

Fanger, P. O. (1970). *Thermal Comfort*. Copenhagen: Danish Technical Press.



D. P. WYON, I. ANDERSEN AND G. R. LUNDQVIST

(*Facing p.* 221)

FINNEY, D. J. (1947). *Probit Analysis*. Cambridge University Press.
FOX, R. H., LÖFSTEDT, B. E., WOODWARD, PATRICIA M., ERIKSSON, E. & WERKSTRÖM, B. (1969). Comparison of thermoregulatory function in men and women. *Journal of Applied Physiology* **26**, 444–53.
HOLMBERG, I. & WYON, D. P. (1969). The dependence of performance in school on classroom temperature. *Educational and Psychological Interactions*, no. 31, 20 pp. School of Education, 200 45 Malmö 23, Sweden.
JONCKHEERE, A. R. (1954). A distribution-free *K*-sample test against ordered alternatives. *Biometrika* **41**, 133–45.
MANDORFF, S. (1971). Calculation of the frequency of high room temperatures as a result of hot outdoor climate. *Proceedings of the 5th International Congress for Heating, Ventilating and Air-conditioning, Copenhagen* **1**, 41–63.
SIEGEL, S. (1956). *Nonparametric Statistics*. New York: McGraw-Hill.
Statistisk Årbog [*Statistical yearbook*] (1969). Copenhagen: Danmarks Statistik.
STOLWIJK, J. A. J. (1969). Thermoregulatory responses of men and women at rest to sudden changes in environmental temperature. *Biometeorology* **4**, 28–9. (Abstract only.)
WINER, B. J. (1962). *Statistical Principles in Experimental Design*. New York: McGraw-Hill.
WYON, D. P. (1969). The effects of moderate heat stress on the mental performance of children. *National Swedish Institute for Building Research*, no. D 8/69, 83 pp.
WYON, D. P. (1970*a*). Studies of children under imposed noise and heat stress. *Ergonomics* **13**, 598–612.
WYON, D. P. (1970*b*). Conséquences de la température sur l'éveil et l'effort dans le travail intellectuel [The effects of temperature on arousal and effort in mental work]. *Cahiers de l'Association Française de Biométéorologie* **3** (2), 16–21.
WYON, D. P., LIDWELL, O. M. & WILLIAMS, R. E. O. (1968). Thermal comfort during surgical operations. *Journal of Hygiene* **66**, 229–48.

EXPLANATION OF PLATE

Four female subjects in cotton suits (0·7 clo) in the climate chamber during an experimental session. On the table the dial vote units are seen, together with material for psychological tests. Only sedentary activities were performed.