
SURVEY OF SUBJECTIVE RESPONSES TO THE THERMAL ENVIRONMENT IN OFFICES

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ABSTRACT

The reactions of 26 subjects to the thermal environment in a commercial building throughout the working day have been monitored for one year. This paper describes the instrumentation and the results obtained from the survey.

The results show that each category of the Bedford comfort scale does not cover equal temperature intervals, the central, comfortable, category being more than twice as wide as the others. The preferred temperature of the occupants of the building was 22.0^{o}C which is in fairly good agreement with that predicted by Fanger's comfort equation (22.6^{o}C). Away from the region of the optimum thermal environment the difference between the comfort equation and the survey results was much greater.

If as a design criterion the maximum number of complaints that would be acceptable from the occupants of a multi-occupancy office is 10% the survey shows that the temperature throughout the office should be within the range 20-23^{o}C.

The paper compares the reaction of the subjects during the summer and winter and morning and afternoon and that between men and women. Also investigated was the difference in clothing habits between men and women throughout the year.

1. INTRODUCTION

Studies of an individual's response to his or her thermal environment have, in the past, generally been carried out in specially constructed test rooms. So as to relate results obtained in these somewhat unusual environments with those found in the normal situation, it was decided to undertake an experiment in which an individual's response was monitored at his or her place of work. The study would help to build a picture of individual thermal requirements over long time periods.

The parameters which basically define the thermal environment are:-

(a) the mean air temperature
(b) the mean radiant temperature
(c) the relative humidity
(d) the mean air speed.

The objective, therefore, was to monitor the thermal environment in which a person was situated, and to register that person's assessment of his or her environment on a seven point voting scale. Thus, personal evaluations of the working thermal environment was obtained over the four seasons. This information has been used to determine:-

(a) the variation in the thermal requirements of people due to season and
(b) how equations formulated to predict individual responses to a particular environment perform in reality.

In order to carry this out a number of monitoring stations which measure the environmental parameters of dry bulb temperature, wet bulb temperature, mean radiant temperature and air speed have been established within Watson House. Associated with each of these monitoring stations were voting boxes, to record an individual's impression of the thermal environment at selected intervals of time throughout the working day for a year.

In addition to these individual stations, measurements of the building's external ambient dry and wet bulb temperatures were made, so that correlations could be carried out with both the internal and external conditions, as both of these variables could affect an individual's overall assessment.

2. ORGANISATION

To obtain a representative sample of both individual's responses and diversification of environments, a range of locations was required around the building comprising both offices and laboratories, some of which were air conditioned and other naturally ventilated. Sites were chosen where, it was anticipated, a range of differing thermal environments would be naturally evident, but no attempt was made to modify these conditions in any way. Twenty-six suitable locations were chosen. Volunteers (nineteen males and seven females) within these locations were asked to participate in the study.

In addition, the subjects were asked to complete a weekly clothing questionnaire, as this variable was likely to affect their comfort sensation and would change during the course of the year's investigation. Due to the difficulties involved in measuring metabolic rate, this value was estimated at 80 W/m^2 ($\doteq$ 70 $Kcal/hr\ m^2$) for each subject.

3. INSTRUMENTATION

At hourly intervals, between 9.30 and 16.30 the central control system was arranged to initiate a two minute voting period, during which time the subject was requested to register a vote corresponding to one of the seven positions on the seven point "Bedford" scale (Appendix 1). The votes were stored in a purpose-built control cabinet logic rack. After the two minute period the votes and associated environmental parameters were recorded.

The external temperature and humidity were measured with an Ultrakust psychrometer mounted within a Stevenson's screen placed on the roof of the building. These parameters were measured each time a scan of the individual monitoring stations was completed.

In order that the external psychrometer and the aspiration systems of the monitoring stations were activated before the recording of data, the control cabinet turned these units on one minute before the voting period commenced.

To ensure that as many subjects as possible voted at the required time, a warning lamp and buzzer were activated at the commencement of the voting period. The lamp remained on for the two minute voting period or until the subject had voted.

If the subject recorded an erroneous vote, a cancel, or reset switch was provided which set the vote signal to zero so that the subject was able to vote again without recording the error.

The voting box is shown on the left hand side of Fig. 1. The lamp is clearly visible as are the seven voting and cancel buttons.

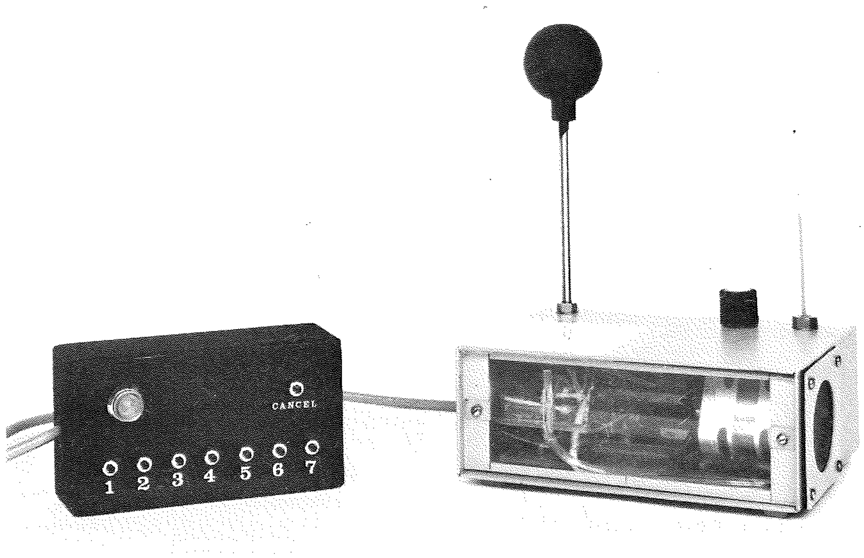


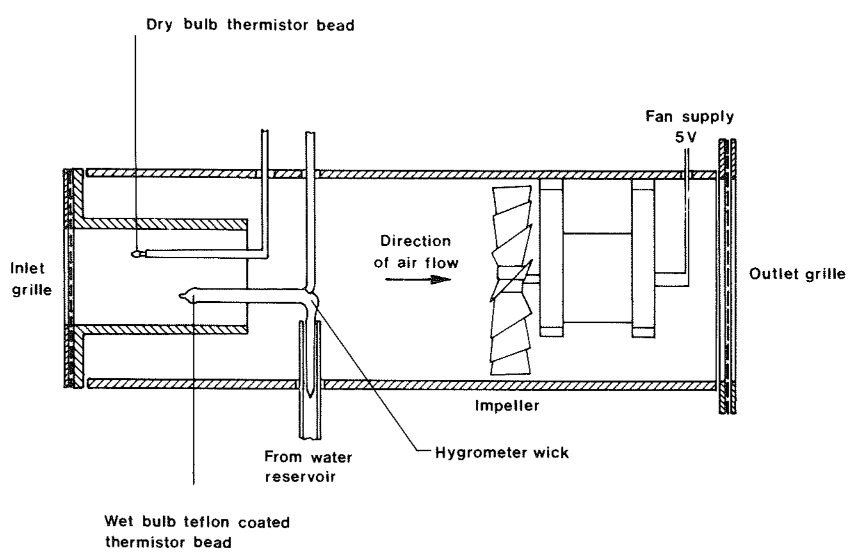
Fig. 1. Monitoring station and voting box units.

The monitoring station is shown on the right hand side of Fig. 1. and has been designed to measure the environmental parameters, with the use of precision thermistors. The temperature and air speed measuring circuits have been described elsewhere[1].

Measurement of the air speed is achieved by heating a thermistor with a current of approximately 3 mA. In the bridge circuit used, this causes the thermistor bead to dissipate 18 mW of power, which is sufficient to raise its temperature by approximately 9 degrees Celsius. When air passes over the bead it is cooled, and the thermistor resistance changes.

These anemometers have to be individually calibrated. The bead is mounted so that it just projects from the end of a nylon tube mounted on the right hand side of the station. This permits the bead to detect omnidirectional air speeds, and prevents the support from interfering in the measurement to any great extent.

The dry bulb temperature and wet bulb temperature thermistors are mounted inside the monitoring station so that air may be drawn over them to provide correct readings. Fig. 2 shows the method by which the two thermistors are mounted, and this arrangement can be seen in Fig. 1. The fan draws air from outside the unit over the two thermistors for five minutes commencing one minute before the start of the voting period. This allows the thermistors sufficient time to equilibrate as the wet bulb requires about two minutes for the correct depression to be achieved.



MONITORING STATION ASPIRATION SYSTEM

Fig. 2. Monitoring station aspiration system.

Mean radiant temperature is calculated from measurements of air temperature, globe temperature and air speed using the equations developed by Kuehn, Stubbs, Weaver[2]. It was decided that a 2 in dia globe would be best suited to the requirements from the point of view of size, and ancillary tests showed these to produce no significant decrease in accuracy compared with a standard 6 in diameter globe. The globe thermistor bead was mounted at the centre of the 2 in diameter globe, which was painted matt black.

The buzzer that provided the auditory cue to the subject was mounted within the monitoring station.

4. PROCEDURE

The two units, the monitoring station and voting box were placed in close proximity to the individual's normal work place, usually on his desk. They were instructed to ignore the monitoring station as only the voting box required their attention.

The subjects were asked to register their overall appraisal of conditions at hourly intervals during the day. At the same time as the votes were recorded the ambient environmental conditions of each of the stations were monitored. Thus each vote was accompanied by the corresponding dry bulb, wet bulb and globe temperatures and air speed. In addition, the external ambient conditions as monitored by the psychrometer on the roof of the building were recorded.

5. DATA

A computer program was written to translate the voltage signals into engineering units and the appropriate subjective vote. This program incorporated the individual calibtations of each anemometer. A further program was also written to calculate the value of Fanger's predicted mean vote[3] for each set of measured environmental parameters, taking into account estimates of each subject's clothing insulation and activity level.

6. RESULTS

6.1. Clothing

From the weekly clothing questionnaires filled in by each subject the thermal insulation of their clothing was estimated using the data of Seppanen[4]. Fig. 3 shows the variation of average weekly clothing insulation with external temperature. As would be expected the clothing insulation falls with increasing external temperature. These results indicate the large difference in clothing habits between men and women. At low temperatures the clothing of both sexes has similar insulation. Women, however, have a greater flexibility in their choice of clothing and therefore are able to compensate for the higher summer external temperatures to a greater degree than can men. This difference in clothing habits may cause problems of temperature control in offices occupied by both men and women during the summer.

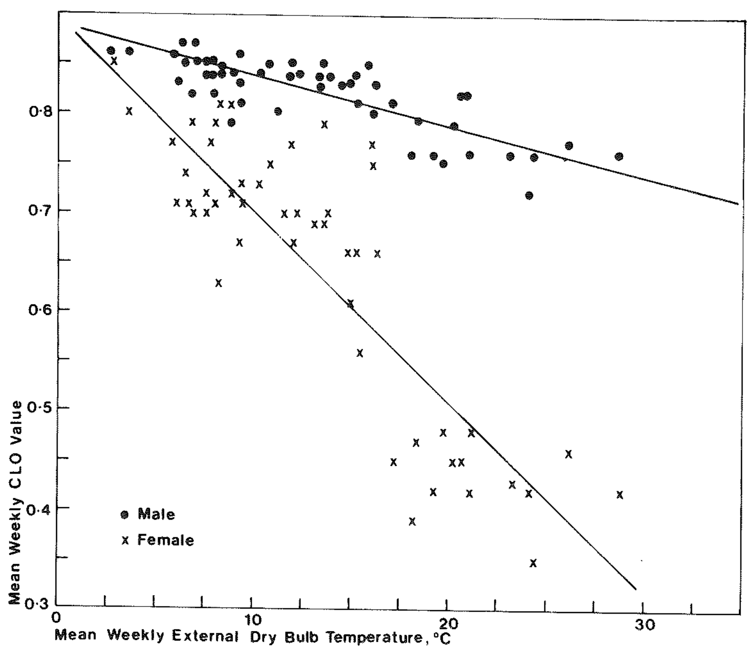


Fig. 3. Variation of average weekly clothing insulation with external ambient temperature.

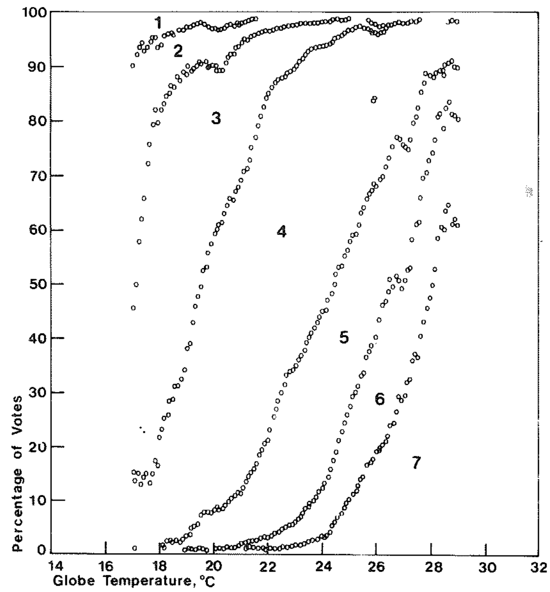
6.2. Preferred Temperature

6.2.1. Analysis into proportions

The variation of the proportion of votes in each category of the Bedford scale with globe temperature is shown in Fig. 4. This shows that at 22°C for example

1%	of	the	votes	recorded	were	7
3%	"	"	"	"	"	6 or 7
21%	"	"	"	"	"	5, 6 or 7
85%	"	"	"	"	"	4, 5, 6 or 7
97%	"	"	"	"	"	3, 4, 5, 6 or 7

99% of the votes recorded were 2, 3, 4, 5, 6 or 7



VOTE DISTRIBUTION

Fig. 4. Variation of proportion of votes in each category of the Bedford scale with globe temperature.

From this type of analysis the transition temperature between successive voting categories can be determined from successive 50% levels, i.e. the transition from vote 3 to vote 4 occurs at that temperature where half of the recorded votes were 3 or below and half were of 4 and above. Similarly the transition between votes 4 and 5 occurs at the temperature where half of the votes were 4 or below. The preferred or neutral temperature, i.e. the temperature giving an average vote of 4, is then the mid point of category 4. The results are shown in Table 1.

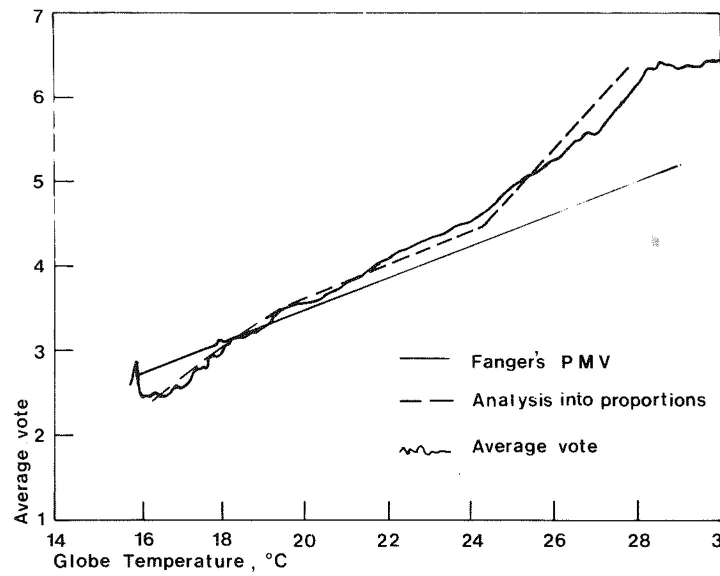
The table shows that the temperature range covered by the central, comfortable category is 4.9°C whilst for the comfortably warm and too warm categories (votes 5 and 6 respectively) the ranges are 2.0°C and 1.5°C. Because of the small number of votes collected at temperatures below 19°C it was not possible to determine accurately the transition temperature between votes 2 and 3. However, the results indicate that the width of the comfortably cool band (category 3) is approximately 2.5°C. The relative narrowness of categories 3, 5 and 6 compared to the central one indicates that when the temperatures of the environment departs from the comfort zone (i.e. the temperature range corresponding to a vote of comfortable) dissatisfaction becomes rapid.

6.2.2. Average vote

Because the width of each category is not the same it is not possible to fit a linear regression line, having a constant slope to the data over the whole temperature range. Since the analysis into proportions does not require any assumption on the relative widths of the scale the results quoted in this paper are obtained from this method. However, visual comparisons between the data collected from different sub sets of the data, e.g. summer and winter or male and female, cannot easily be made with this method. Therefore, the variation of the average vote of the subjects with globe temperature has been used.

The variation of average vote with temperatures is shown in Fig. 5 for the whole sample. This graph again emphasises, by the steepness of the slope at temperatures above 24°C, that when the temperature deviates from the comfortable region the subjects react strongly and tend to register their disapproval.

Also plotted is the results from the analysis into proportions. This graph assumes that the transition between votes 3 and 4 is equivalent to a vote of 3.5 and that between 4 and 5 is equivalent to a vote of 4.5. This method gives slightly different results to that obtained from the plot of average vote because median vote is used instead.



COMPARISON OF PREDICTIONS FROM FANGER'S COMFORT EQUATION AND THE RESULTS OF THE WATSON HOUSE SURVEY

Fig. 5. Variation of average vote with temperature for the whole sample compared with Fanger's comfort equation.

6.3. Comparison With Comfort Equation

One of the objects of the survey was to determine whether predictions based on theoretical and climatic chamber experiments were valid in practical situations. A computer program was therefore written to evaluate Fanger's Predicted mean vote (PMV) (3) for every environment in which a vote was recorded. The program used the environmental parameters of the thermal environment together with the clothing insulation estimated from the weekly clothing questionnaire. A value of 80 W/m^2 ($\hat{=}$70 $kcal/hr\ m^2$) was assumed as the metabolic rate for all of the subjects.

Analysis of the predicted mean votes showed that they followed a linear relationship with globe temperature. Consequently a least squares regression line relating predicted mean vote to globe temperature was calculated. This is shown in Fig. 5.

Although a different voting scale was used in the survey to that used by Fanger (Bedford cf ASHRAE) the available evidence indicates that both behave in a similar manner.

Comparison between the actual and predicted results show that within the region of the optimum thermal environment (equivalent to votes of between 3.5 and 4.5) the comfort equation predicts a vote approximately 0.15 units lower than that found from the survey. Outside of this zone the comfort equation greatly underestimates the warmth of the subjects at high temperatures and overestimates it at low temperatures. Thus, in a real situation people are more critical of uncomfortable conditions than predictions based on tests in artificial climates suggests.

Within the region of the optimum environment, where agreement between the results of the survey and the comfort equation is reasonable the equation predicts a neutral temperature of 22.6°C compared to 22.0°C from the survey. This difference could be due to underestimating the activity level of the buildings occupants by approximately 5 W/m^2 or the clothing by 0.1 clo. Because of the sedentary nature of the occupants it is unlikely that their activity level was greater than that used in the comfort equation. Any error is probably in the estimation of the insulation of the clothing, since the estimates were based on American clothing which may be made from different materials than in Britain.

6.4. Individual Variability

Not everyone reacts to the thermal environment in the same way. The variation in the percentage of votes of comfortable (vote 4) and of votes 3, 4 and 5 with globe temperature are shown in Fig. 6. At the optimum temperature of 22°C 60% of the votes cast were comfortable and a further 34% were either comfortably cool or comfortably warm. Assuming that only those people who vote 1, 2 or 6 or 7 suffer discomfort the graph shows that even at the optimum temperature 6% of the population will be dissatisfied, which is in excellent agreement with Fanger's prediction of 5% as the minimum number of people who would be dissatisfied in any one environment[3].

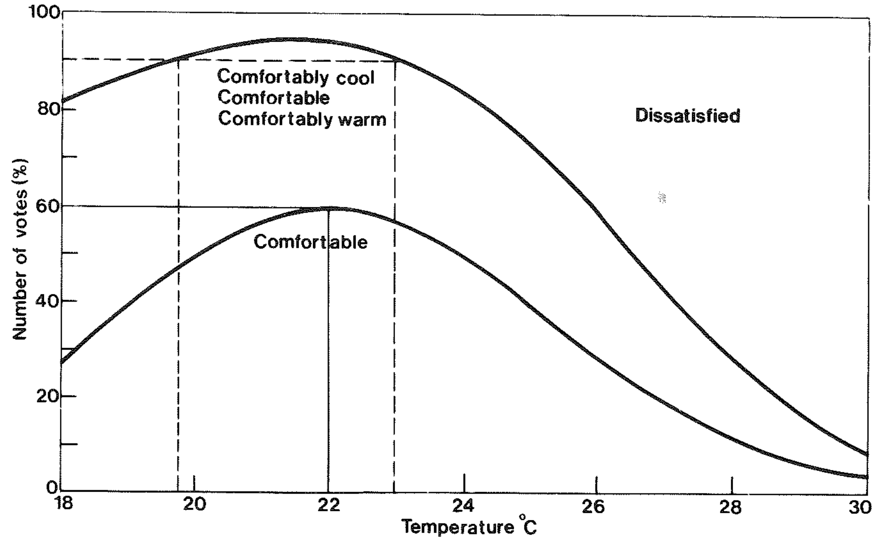


Fig. 6. Variation in percentage of votes of comfortable (vote 4) and of votes 3, 4 and 5 with globe temperature.

This graph indicates that if, as a design criterion, the maximum number of complaints that would be acceptable from the occupants of a multi-occupancy office is 10% then the temperature should be maintained between 20°C and 23°C.

6.5. Effect of Season

It would be expected that due to the lighter clothing worn by the participants in summer, the preferred temperature would be higher in summer than in winter. However, the survey showed that there was very little difference in the preferred temperature (Fig. 7). The graphs also show that temperatures on the warm side of comfortable were judged as being warmer in summer than in winter despite the lower insulation of the subjects clothing. It appears that during the summer the subjects sought refuge from the external climate and if this was not forthcoming indicated their dissatisfaction.

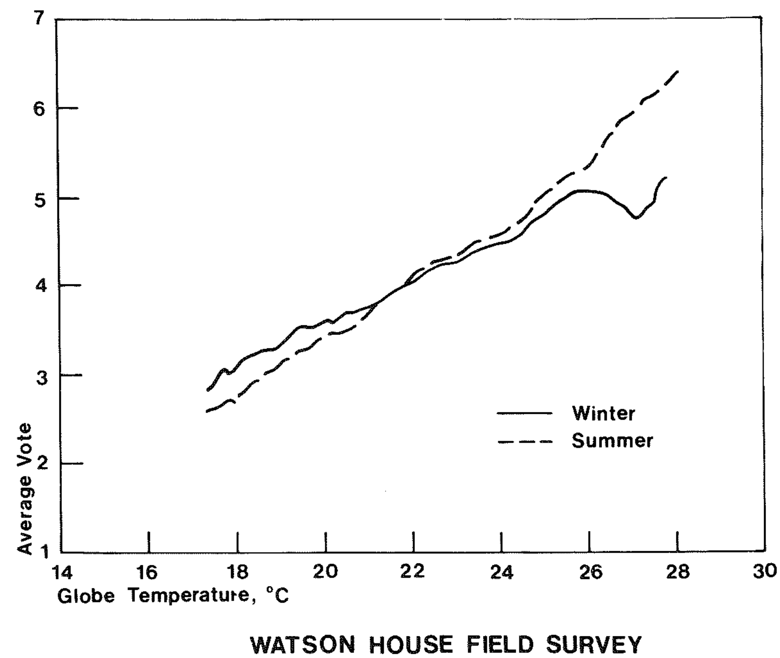


Fig. 7. Variation in average vote with temperature: summer and winter compared.

Humphreys[5,6] in his review of field surveys throughout the world showed that the preferred temperature was related to the average outside temperature and that as the outside temperature increased so did the preferred temperature. As a result he advocated that internal temperatures should be allowed to follow the external temperature and suggests that temperatures as low as 19°C in winter and up to 24°C in summer would be acceptable. The results from the present survey indicate however that if this is put into practice widespread complaints of underheating in winter and of overheating in summer would be voiced by the occupants of the building. Instead our results indicate that the temperature should be maintained at 22°C throughout the year.

6.6. Difference Between Men and Women

The variation of average vote with temperature for males and females is shown in Fig. 8. It would be expected that because of the lighter clothing worn by women the preferred temperature of the females would be higher than for the men. The results however show the opposite: this unexpected result has also been observed by Ballantyne(7).

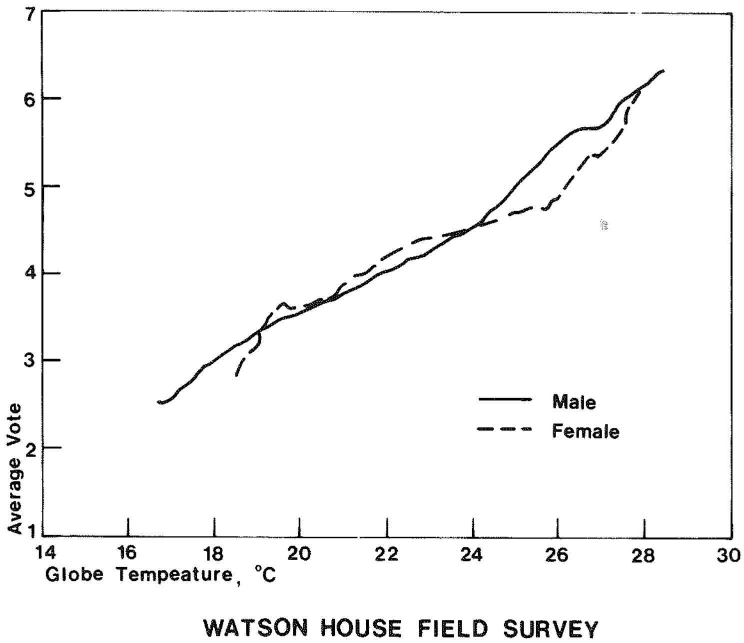


Fig. 8. Variation in average vote with temperature: males and females compared.

The graph shows that between 22°C and 26°C the average female vote rises very slowly with increasing temperature. This is in the vicinity of the transition temperature between votes 4 and 5 and indicates that the women were able to adjust their clothing level to compensate for the warm temperatures. Above 26°C the vote again increases with temperatures when the limit of clothing adjustment has been reached.

6.7. Time of Day

To investigate any effect that the time of day has on people's reaction to the thermal environment a comparison was made of the votes collected during the morning (from 9.30 to 12.30) and in the afternoon (13.30 to 16.30). The results were almost identical suggesting that the subjective reaction to the thermal environment is independent of the time of day. Further analysis of the data on an hourly basis will be made in the future.

7. CONCLUSIONS

1. The temperature ranges covered by each category of the Bedford scale are not of identical width. The centre

comfortable, category covers a temperature range of 4.9°C compared to 2.5°C for the comfortably cool, 2.0°C for the comfortably warm and 1.5°C for the too warm bands.

2. The preferred temperature of the participants in the survey, i.e. the temperature equivalent to a vote of 4, is 22°C and is independent of the time of day.

3. Fanger's comfort equation predicts a comfortable temperature 0.6°C higher than that found from the survey. This difference could be due to incorrect estimates of the subjects clothing. However, away from the region of optimum thermal comfort (equivalent to votes between 3.5 and 4.5) the subjects were less tolerant of the thermal environment than the comfort equation predicts.

4. At the optimum temperature of 22°C, 6% of the population were dissatisfied with the environment.

5. If, as a design criterion, a limit of 10% is chosen as the maximum number of dissatisfied occupants that is acceptable in a multi-occupancy office the temperature should be maintained within the range 20°C to 23°C.

6. The preferred temperature in winter is the same as that in summer despite the change in clothing habits. However, higher than preferred temperatures tend to be judged as being warmer in the summer than in the winter.

7. The female subjects taking part in the survey preferred a slightly lower temperature than the males (21.7°C cf 22.0°C). The greater flexibility of their clothing however allows women to adapt to higher temperatures to a greater extent than can men.

8. The survey has shown that people react strongly if the environmental conditions fall outside the comfort zone.

8. REFERENCES

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TABLE 1. TRANSITION TEMPERATURES

SET	2/3	3/4	4/5	5/6	6/7	NEUTRAL
ALL	17.0	19.5	24.4	26.4	28.0	22.0
Summer	17.1	19.8	24.0	26.0	27.5	21.9
Winter	-	19.4	24.8	-	-	22.1
Male	17.0	19.6	24.4	26.0	-	22.0
Female	-	19.0	24.4	27.4	28.0	21.7
Morning	-	19.4	24.4	26.4	27.9	21.9
Afternoon	-	19.6	24.4	26.6	28.0	22.0

\- Insufficient data

APPENDIX 1

VOTING SCALES

BEDFORD		ASHRAE
Much too cool	1	Cold
Too cool	2	Cool
Comfortably cool	3	Slightly cool
Comfortable	4	Neutral
Comfortably warm	5	Slightly warm
Too warm	6	Warm
Much too warm	7	Hot

DISCUSSION

F.Grivel,
Centre d'Etudes
Bioclimatiques, F

How can you explain the greater intolerance, outside the optimum temperature region, of the workers you observed compared to people observed in laboratory situations? It seems that the contrary has been reported in other field studies reviewed by Humphreys (Humphreys, M.A., Field studies of thermal comfort compared and applied. Building Research Establishment current paper CP 76/75, August 1975).

D.S.Fishman

The thermal conditions within Watson House were generally maintained within the comfort zone and conditions outside of it were not susstained for long periods. Consequently the subjects did not have time to adjust to these conditions.

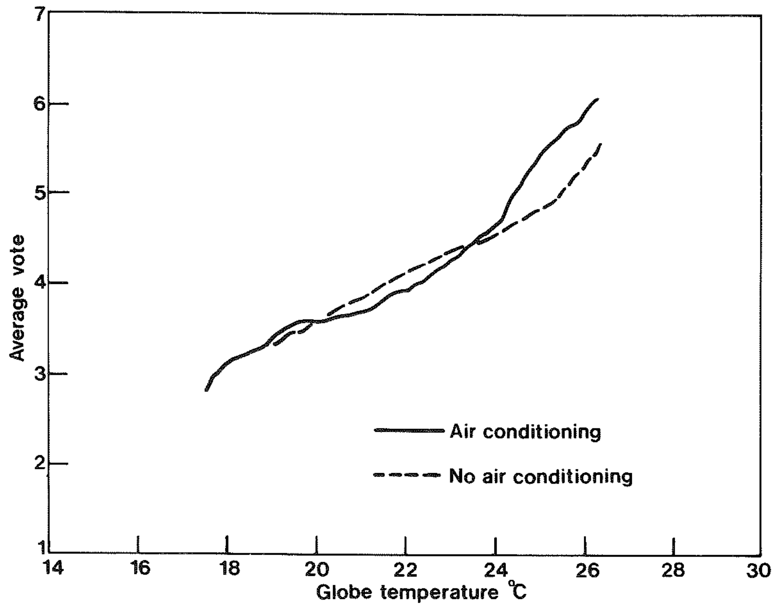
This may explain the difference between our results and Humphreys, although it should also be remembered that Humphreys used averages taken from a large number of field surveys. The Watson House results fall within the ranges covered by these other surveys.

P.Kjerulf-Jensen
Technical University
of Denmark

Has any comparison been made to see if people vote differently in naturally and mechanically ventilated rooms?

D.S.Fishman

The comparison of the variation of average vote with globe temperature for air-conditioned and naturally ventilated offices is shown in Figure A. These results indicate that the people in air-conditioned offices are less tolerant of temperatures above 24°C than those in naturally ventilated offices. Since only seven of the subjects worked in air-conditioned areas and temperatures above 24°C were not often encountered, these results should be treated with some caution. However, the indications are that people in air-conditioned areas expect a higher standard in the thermal environment and are more likely to protest if these are not met.



WATSON HOUSE SURVEY
AVERAGE VOTE FOR GIVEN GLOBE TEMPERATURE
FIG.A

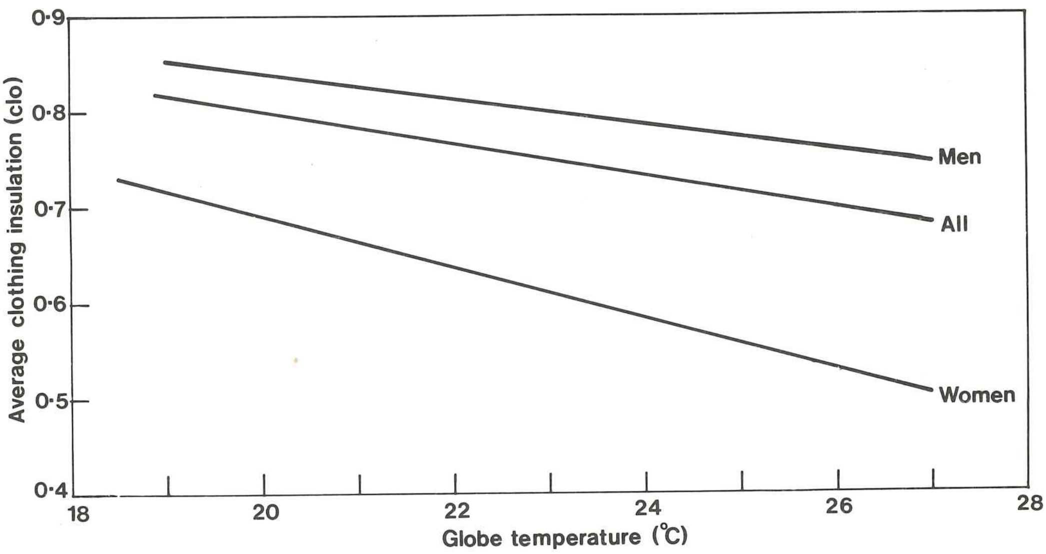
J.Lebrun
Université de Liège, B

It is possible to find near neutrality a good agreement between the thermal comfort equation and experiments, if you use the right value of metabolism. This morning I mentioned a value of 78 W/m^2 for our experiments with sedentary subjects engaged in mental activity. Of course the agreement between 80 and 78 W/m^2 is very good.

Can you specify the clothing value used when calculating the PMV (see the straight line in fig. 5)?

D.S.Fishman

With reference to the line relating PMV to globe temperature: each time a vote was recorded the appropriate value of PMV was calculated from the measured environmental parameters and the subjects' clothing insulation estimated from the weekly clothing questionnaire. A regression line was then calculated relating the value of PMV with globe temperature (correlation coefficient: 0.70). Thus, the line does not refer to one particular clothing ensemble, but takes into account the changes made by people in response to changes in climatic conditions. Figure B shows the variation in average clothing level with internal temperature.



VARIATION OF AVERAGE CLOTHING INSULATION WITH INTERNAL TEMPERATURE

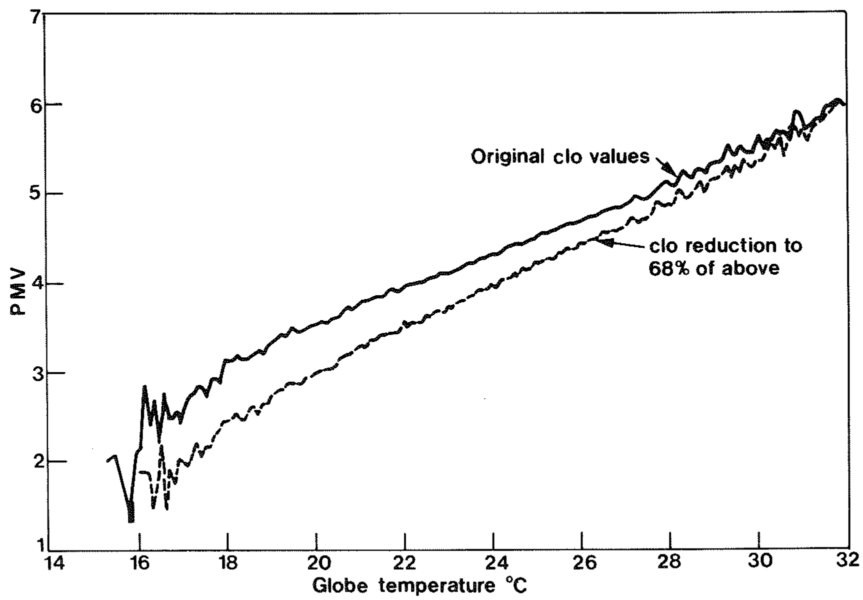
A.P.Gagge
John B.Pierce
Foundation Lab., USA

In ASHRAE Trans., Vol. 82 (2), 1976, Dr. Nishi described a comparison of clo measurement by the Sprague-Seppanen-Nevins (SSN) integrated method and our direct clo measurement based on the measurement of clothing, surface, skin and ambient air temperature. We found that the SSN system was very consistent but the direct measures by Nishi's system (ASHRAE, Vol. 80 (2), 1974) were 68 % the SSN values. It is interesting to note that Dr. Olesen in the previous paper also found lower integrated values compared to the Sprague (SSN) system by using the Fanger clothing weight/insulation relationship for summertime clo. With this correction at 25° the clothing for comfort (in fig. 3), would have been approx. 0.8 x 0.7 or approx. o.55 clo, which value would be well in line with our USA measurements. Perhaps this would explain the difference between your results and Fanger's equation prediction.

D.S.Fishman

It is always difficult to estimate the thermal insulation of clothing worn by people taking part in surveys, especially when the estimates are based upon measurements carried out in a different country. The values used are therefore subject to errors.

Following the comments of Gagge we have re-analysed our data, reducing the estimated clo values by 32 % (Fig. C). These results show that even larger discrepancies between the survey results and the comfort equation occur, the difference in neutral temperature being increased from 0.6°C up to 2°C. For our subjects responses to agree with Fanger's predictions, the clothing insulation values would have to be increased by approximately 13 %.



VARIATION OF PMV WITH INTERNAL TEMPERATURE