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The Effects of Air Temperature and Relative Humidity on Thermal Comfort in the Office Environment

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Abstract

The objective of this study was to assess the effect of air humidification and temperature on thermal comfort in sedentary office work. A blinded twelve-period cross-over trial was carried out in two similar wings of an office building, contrasting 28–39% steam humidification with no humidification, corresponding to 12–28% relative humidity. The length of each period was one working week. The study population was 169 workers who judged their thermal sensations in a weekly questionnaire. The percentage of dissatisfied was lowest when the air temperature was 22 °C. At 22 °C an increase in relative humidity raised the mean thermal sensation only slightly. At 20 °C when the air was humidified there were fewer workers who judged their air temperature as being too low. On the other hand, at 24 °C humidification increased the percentage of workers who judged their air temperature to be too high. The percentage of dissatisfied increased rapidly when the air temperature was outside of its optimum value, 22 °C. The percentage of workers complaining about draft increased when the air temperature was lower than 22 °C. Thus we consider that the temperature range from 20 to 24 °C during wintertime may be too wide without individual temperature control from the point view of thermal comfort. We recommend that the air temperature should be kept between 21 and 23 °C if no individual control is available. The best solution would be individual temperature control permitting adjustment of the temperature at 22 ± 2 °C.

KEY WORDS:
Air temperature, Relative humidity, Thermal comfort, Draft, Office environment, Field study

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Introduction

Standards for maintaining comfortable indoor thermal environments have been developed by international and national organizations. Two most common standards, the ASHRAE Standard 55–92 and ISO Standard 7730, are both based on a strong foundation of extensive research under laboratory conditions. Equations have been developed, based on these experiments, to predict the average thermal sensation felt by a large group of people exposed to a given set of thermal conditions. Most of the international (ASHRAE 55–92, 1992; ISO 7730, 1984; NKB, 1981) and national (DIN 1946, 1993; Indoor climate and ventilation in buildings D2, NBC, 1987) thermal environment standards recommend a 20–24 °C operative temperature for sedentary office work during the heating period. Table 1 shows their design criteria. The basic design values are 1.2 met and 1.0 clo. According to the comfort equation, the predicted percentage of dissatisfied (PPD) should not exceed 5% when the temperature has its optimum value and the PPD will be less than 10% in the upper and lower temperature limit. In practice, the percentage of dissatisfied will be higher than 5% due to individual differences in metabolism and clothing.

According to a Finnish study in several office buildings (Kähkönen et al., 1990) it was easy to meet the requirements of ISO 7730 during winter. However, in spite of this, a draft sensation was very common among workers.

The metabolism in sedentary office work can be between 1.0 and 1.4 met (Schiller et al., 1988). This requires a ± 2.0 °C individual adjustment zone on both sides of the optimum air temperature.

In Finnish offices the mean clo-value of typical indoor office wear in winter has been estimated at between 0.5 and 0.75 (Kähkönen, 1991). These values are clearly lower than the design values used in most standards (Table 1). However, they do not take into account the insulation effects of office furniture. We have measured with a thermal manikin the insulation value of a typical office seat to be about 0.2 clo.

A Finnish cross-sectional study (Jaakkola et al., 1989) among offices workers showed a large percentage of dissatisfied with a thermal environment at both 20 °C and 24 °C. The present study was part of a larger research project concerning the effects of relative humidity on symptoms and perceived air quality in the office environment (Reinikainen et al., 1992; Reinikainen and Jaakkola, 1993). The objective of the study was to determine the optimum value of the air temperature for office workers during the heating period, the need for individual temperature control, and the effect of air humidification on thermal comfort at different temperatures.

Methods

Building and Study Population

Pasila Office Center, located in the center of Helsinki, was known from earlier studies carried out there (Jaakkola et al., 1989; Reinikainen et al., 1992). The building and its ventilation system have been described in detail (Reinikainen et al., 1992). All of the 2150 workers in the building were employed in various government agencies. All the persons taking part in this study worked in small office rooms designed for 1–3 persons. The building was constructed in 1981, and was completely equipped with mechanical ventilation with heat recovery. The structure of the building, a double-E with 6 symmetric wings, formed an ideal environment for experimental study. The supply air is ducted into the corridors of each floor in each wing. The supply airflow is designed for summer cooling with outdoor air. Each room has at least two exhaust air registers. The mean exhaust airflow is 1.8 $l/s \cdot m^2$ per floor area and 25 l/s per occupant. The supply air temperature during winter is near 20 °C. This ventilation system does not permit individual control of the thermal climate, but all the windows in the rooms are openable. For the purpose of the experiment, steam humidification equipment was installed in two identical wings. The orientation of the rooms is either east or west, which eliminates the heating effects of the solar radiation on the room air temperature during the winter.

Table 1 Design values of the thermal climate for an office room in winter.

Source	Design presumptions	Temperature (°C)	Mean velocity (m/s)
NKB 1981 and ISO 7730	1.2 met/1.0 clo	20–24	≤0.15
NBC 1987	office work	21*/20**	≤0.18
ASHRAE 55-1992	≤1.2 met/0.9 clo	20/22/23.5	≤0.15
DIN 1946	1.0–1.5 met/0.5–1.0 clo	22–25	0.15–0.19

*) Air temperature **) Operative temperature

The source population consisted of 369 workers in the two wings. The eligibility criterion applied for participation was: no anticipated absence from work due to vacation, travel or other reason during the study period. Altogether 200 workers were excluded from the study; 116 (31%) subjects were not eligible because of an anticipated absence, 74 (20%) refused to participate and the remaining 10 (3%) subjects did not return the baseline questionnaire. Those 169 workers who were willing to participate and returned the baseline questionnaire were entered in the trial. The characteristics of the study population are described in Table 2.

Experimental Procedure

The experiment was carried out during winter 1989–90 (December-February). The experiment consisted of a 12-period cross-over trial, the length of each period being one week. The workers were divided into two study groups working in different but otherwise similar wings. At the baseline, there

Table 2 Characteristics of the study population

	Wing A (n=92)		Wing B (n=77)		Total (n=169)	
	n	%	n	%	n	%
Age						
–24		–	2	2.6	2	1.2
25–34	20	21.7	20	25.9	40	23.7
35–44	35	38.1	29	37.7	64	37.8
45–54	28	30.4	18	23.4	46	27.2
55–	9	9.8	8	10.4	17	10.1
Gender						
Male	53	57.6	38	49.4	91	53.8
Female	39	42.4	39	50.6	78	46.2
Professional education						
None	14	15.2	13	16.9	27	16.0
Course	8	8.7	6	7.8	14	8.3
Vocational	4	4.3	8	10.4	12	7.1
College	16	17.4	17	22.1	33	19.5
University	50	54.4	33	42.8	83	49.1

was no humidification. During the first week, the relative humidity in wing A was raised to 28–39%. Simultaneously, wing B was non-humidified, with a relative humidity of 12–28%. During the weekend, the humidification was changed so that during the second week wing B was humidified while wing A was non-humidified. The same "cross-over" was repeated 10 times. Each worker was exposed during the six one-week periods to humidified and non-humidified air.

Data Collection and Analysis

The exhaust airflow, air temperature and relative humidity in each room were measured at the beginning of the study. The difference between the operative and air temperatures during the heating period was found to be less than 0.5 K also in the earlier study (Seppänen and Jaakkola, 1989) when the outdoor temperature was lower than during this study, so the values of the operative temperature were no longer measured. The temperature and relative humidity were measured continuously in three rooms in both wings.

At the baseline the workers filled in a questionnaire inquiring about symptoms and perceptions during the past 12 months and details of the work environment.

The workers' clothing insulation was not estimated. It was, however, typical of that worn for winter office work in Finland (Kähkönen, 1991), the office chair including no more than 1.0 clo. The main activity in the building was seated office work with metabolism between 1.1 and 1.4 met. The workers daily spent 7 hours (median) in the building and 6 hours in their own rooms.

The participant were asked to fill in a self-administered questionnaire once a week on Wednesday or Thursday after work indicating whether they had any symptoms and environmental complaints such as unpleasant odor, stuffiness, draft, dryness and temperature sensation. The air temperature was checked by the occupant from a calibrated thermometer distributed by the researchers. The reading accuracy of the thermometer was 0.5 °C. The questions and rating scales for temperature and draft were:

- Temperature: How did you experience the temperature in your room today? 0 = all to cool, 1 = too cool, 2 = acceptable, 3 = too warm and 4 = all too warm.
- Draft: Did you suffer any draft in your room today? 0 = not at all, 1 = very little, 2 = slightly, 3 = to some extent, 4 = much and 5 = very much.

The rating scales were a visual analogue with markings from 0 to 4 or from 0 to 5. The subjects were free to mark any point between the end points. The value of each rating was obtained by measuring the distance between zero and the mark.

It is very common to assess the acceptability of thermal climate by assuming that certain votes of thermal sensation on a 7-point scale (ISO 7730) correspond to dissatisfaction. On a 7-point scale (1 = cold and 7 = hot) votes between 3 and 5 are classified as "satisfied" or "acceptable". This represents one-third of the whole area of the scale. We therefore decided to divide our rating scale for the acceptability of the air temperature (range 0–4) into three equal parts and subjective ratings between 0 and 1.33 were classified as "too cool". Similar ratings between 2.66 and 4 were classified as "too warm" and the rest of the scale (1.33–2.66) as "acceptable".

The questionnaires were recorded and analyzed with the SAS-computer package (SAS, 1988). The effect of humidification was evaluated by comparing the percentage of workers who experienced the air temperature as too cool, too warm or acceptable, during humidified and non-humidified periods while the air temperature remained constant. The temperature ratings were calculated for different temperature categories separately for humidified and non-humidified conditions.

Results

Experimental Conditions

The mean daily outdoor temperature during the study was between − 16 and 6 °C. The value of the self-measured air temperature varied in individual rooms from 17 to 28 °C. The mean value was 22.6 °C (SD 1.2 °C) and the median value 23 °C. Of the 1631 responses, 94% showed measured values of air temperatures between 20 and 24 °C. The mean value of the temperature (22.7 °C) was 0.2 °C higher during the humidified period than during the non-humidified period (22.5 °C). The mean value of the air velocity in the offices was very low, 0.05 m/s or less. The vertical temperature difference and the radiant asymmetry due to cool windows were far below limits given in ISO 7730 (3 and 10 K). In the rooms with continuous temperature recording, the mean value of the air temperature was 22.7 °C

(SD 0.7 °C). The mean value of the difference between the daily maximum and minimum temperature was 0.6 °C.

During the non-humidified period the relative humidity was 12–28%, and during the humidified period, 28–39%. The difference was smallest during the last four weeks due to a rise in outdoor air temperature.

Participation

All the 169 participants returned at least one questionnaire from both the humidified and the non-humidified phase. There were altogether 1637 acceptable questionnaires and 1631 temperature readings.

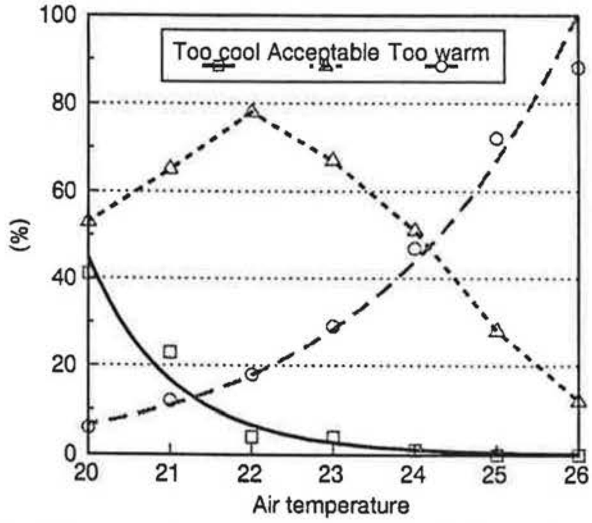

Fig. 1 The percentage of workers who judged their room temperature too cool, too warm or acceptable, as a function of air temperature.

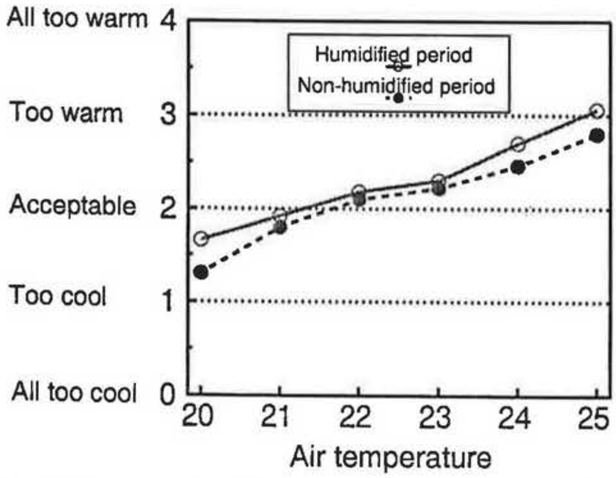

Fig. 2 The mean value of the temperature rating during humidified and non-humidified periods as a function of air temperature.

Thermal Comfort

There were only two workers whose daily air temperature remained stable during the whole period. The others had at least two different temperature observations in their rooms. The mean value of the air temperature ratings was 2.22 with SD 0.64 which means that more of the rooms were too warm than too cool. Of the 1631 temperature ratings, 7.1% could be classified as "too cool" and 25.9% as "too warm". Most of the temperature ratings given by the workers were classified as "acceptable" (67%). The highest percentage of workers whose air temperature was acceptable (78) was recorded when the air temperature was 22 °C (Figure 1). There were still 1% of workers who judged their room too cool at 24 °C and 6% who judged their room too warm at 20 °C (Figure 1).

Draft sensation was not a common problem in this building. The mean draft rating was 0.4 (range 0–5) with SD 0.8. More than 70% of the individual ratings were "no draft sensation at all". Only 6.5% perceived at least some draft (rating between 3 and 5). The mean velocity in the rooms was too low to cause any draft sensation according to the commonly used draft equation (Fanger et al., 1988). A clear sense of draft was relatively uncommon in rooms where the air temperature was 22 °C or more (Table 3). The percentage of workers with no draft sensation decreased rapidly below 22 °C.

Air Humidification and Thermal Comfort

The effect of humidification on the percentage of workers who felt that the air temperature was too cool, too warm or acceptable is shown in Table 4. The humidification had no significant effect on reported thermal comfort when the air temperature was 22.0–22.9 °C. The higher relative humidity decreased the percentage of workers judging the thermal conditions in their room as too cool in the tem-

Table 3 The percentage of workers whose draft vote was 0 or 3–5.

Air temperature (°C)	Percentage of workers (%)	
	Draft vote 0	Draft vote 3–5
20	39	29
21	60	15
22	73	3
23	73	5
24	83	4
25	96	0
26	100	0

Table 4 The percentage of workers whose air temperature rating was too cool, too warm or acceptable during humidified (Hum) and non-humidified (Non) periods.

Temperature rating	Air temperature (°C)											
	20–20.9		21–21.9		22–22.9		23–23.9		24–24.9		25–25.9	
	Hum	Non	Hum	Non	Hum	Non	Hum	Non	Hum	Non	Hum	Non
Too cool	32*	46	21	24	1	4	2	3	1	1	0	0
Acceptable	53	54	68	66	81	83	68	72	45	60	16	29
Too warm	15	0	11	10	18	13	30	25	54**	39	84	71
Number of answers at each temperature range	34	46	102	106	199	240	247	275	157	103	32	21

*) $p<0.10$; **) $p<0.01$.

perature range 20.0–21.9 °C but on the other hand, increased the proportion of workers who judged their room as too warm in the temperature range of 24.0–25.9 °C.

Figure 2 shows the mean values of the temperature ratings as a function of the air temperature during the humidified and non-humidified periods. When the air temperature was 22–23 °C, the mean values of the temperature ratings were almost the same during the humidified and non-humidified periods. When the air temperature was low or high, workers felt the humidified room air warmer than the non-humidified room air.

Discussion

The thermal climate in Pasila Office Center satisfied the requirements of ISO 7730 well. Only 6% of the individual air temperature readings were outside the range of 20–24 °C. However, the average percentage of workers who were not satisfied with their room temperature was as high as 33%. The value of the air temperature at which most of the temperature ratings were acceptable was very close to the value calculated with the comfort equation (ISO, 1984) (1.0 clo, 1.2 met and RH 30%) 22 °C. The measured percentage of dissatisfied in our study was 22%. Furthermore, the PPD value calculated from ISO 7730 will not exceed 10% if the air temperature is no more than ±2 °C outside the optimum value of 22 °C. Based on our results, the percentage of workers who felt the air temperature too low at 20 °C was 40% and too high at 24 °C was 45%.

We did not ask the workers about their thermal sensations using the normal ISO 7-point scale or simply whether they were satisfied or not. The selected criteria for acceptable air temperature ratings (1.33–2.66) seems to be quite satisfactory. A wider (1.2–2.8) part of the rating scale would have decreased the proportion of dissatisfied workers only from 33% to 31%. A narrow definition of acceptability (1.6–2.4) would have increased it from 33% to 38%. On the other hand, such ratings as too warm (3) or too cool (1) cannot be classified as acceptable because after that the mean value of the percentage of dissatisfied would have been only 6% which is the same proportion as temperature readings outside 20–24 °C. Furthermore, at 22 °C the percentage of satisfied would be as high as 98.5%, which is higher than measured in controlled laboratory conditions.

According to laboratory studies, a change in the indoor relative humidity by a +/−10 percent unit will change the value of the optimal air temperature only −/+0.3 °C (Fanger, 1982).

Based on our measurements, the changes of 10 percent unit relative humidity did not affect the satisfaction of workers near the optimum temperature, but the more the air temperature differed from the optimum value, the more the effect increased.

It was not possible to show any other determinants of draft sensation than too low temperature in some rooms. It is possible that the perception of draft refers to the sensation of cool air even without a sensation of air movement.

Our results are consistent with studies carried out under similar outdoor conditions in Sweden and Denmark. The effect of relative humidity levels between 25 and 40% were studied in southern Sweden during winter 1972–1973 in four office buildings with 630 workers (Andersson et al., 1975). The mean temperature level was, however 1 °C higher than in the present study. The metabolism and clothing insulation of the workers were not reported. The percentage of those satisfied with the air temperature was 85% at 21–22 °C and 70–80% at 23–24 °C. These values are higher than those obtained in this study (65–78% at 21–22 °C and 50–70% at 23–24 °C) at the same air temperatures. Contrary to the present study, a change in relative humidity from 25 to 40% at 21–22 °C had no effect on workers' thermal sensation. At 23–24 °C humidification increased the percentage of those whose air temperature was too high from 40% to 60%.

In a Danish library building the mean velocity was the same (0.05 m/s) in the spaces of the workers complaining of draft and workers having no problems vith draft (Berg-Munch, 1979). Such mean air velocities in the rooms were too low to cause any draft sensation. The main determinant of perceived draft was probably the (air) temperature of the workplace, as in our study. When it was lower than 22 °C, over 40% of the workers complained of draft, while the percentage was only 11% in workplaces where the temperature was over 22 °C.

An example from a different outdoor climate is a field study of 2342 workers in 10 San Francisco Bay Area office buildings where the optimum value of the standard effective temperature (SET) was found to be 22.4 °C (Schiller, 1990). The percentage of dissatisfied workers in this temperature was 12%. People disliked conditions above the optimum temperature. Thermal environments below that point were much more acceptable than predicted by the comfort equation.

Conclusions

The results of our study showed that a large proportion of workers (40–45%) can be dissatisfied in offices where the thermal climate meets well the requirements of ISO 7730 (temperature during winter from 20 to 24 °C). The proportion of satisfied (78%) was greatest at 22 °C, which corresponds well with the optimum operative temperature obtained from Fanger's comfort equation. Thus we consider that the temperature range from 20 to 24 °C during wintertime may be too wide without individual temperature control from the point view of thermal comfort. We recommend that the air temperature should be kept between 21 and 23 °C if no individual control is available. The best solution would be individual temperature control permitting adjustment of the temperature at 22 ± 2 °C.

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References

Andersson, L.O.., Frisk P., Löfsteds, B. and Wyon, D.P. (1975) *Human Response to Dry Humidified and Intermittent Humidified Air. An Experimental Study in Large Office Buildings*. Stockholm, Swedish Building Research (R63:1975) (in Swedish, English resume).

ASHRAE (1992) *Thermal Environmental Conditions for Human Occupancy*, Atlanta, GA, American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE Standard 55-1992).

Berg-Munch, B. (1979) "Investigation of indoor climate – a field study", *Dansk VVS*, **15** (9), 34–40 (in Danish with English summary).

DIN (1993) *Teil 2 Raumlufttechnik – Gesundheitstechnische Anforderungen (VDI-Luftungsregeln)*, Berlin, Deutsches Institut für Normung (DIN 1946).

Fanger, P.O. (1982) "The effect of air humidity in buildings on man's comfort and health". Presented at: CISCO Seminar organized with the cooperation of UNESCO: "L'Humidite dans le Bâtiment", Saint-Remy-les-Chevruse.

Fanger, P.O., Melikow, A.K. and Ring J. (1988) "Air turbulence and sensation of draught", *Energy and Buildings*, **12**, 21–39.

International Organization for Standardization (1984) *Moderate Thermal Environments. Determination of the PMV and PPD Indices and Specification of the Conditions for Thermal Comfort*, Geneva (ISO 7730).

Jaakkola, J.J.K., Heinonen, O.P. and Seppänen, O. (1989) "Sick building syndrome, sensation of dryness and thermal comfort in relation to room temperature in an office building: Need for individual control of temperature", *Environment International*, **15**, 163–168.

Kähkönen, E., Virtamo, M., Sunden, M. and Leikas, M. (1990) "It is easy to fulfil the standards of indoor climate". In: Walkinshaw, D.S. (ed.) *Proceedings of Indoor Air '90*, Ottawa, Canada Mortgage and Housing Corporation, Vol. 1, pp. 687–692.

Kähkönen, E. (1991) "Draught, radiant temperature asymmetry and air temperature – a comparison between measured and estimated thermal parameters", *Indoor Air*, **1**, 439–447.

National Building Code of Finland (NBC) (1987) *Indoor Climate and Ventilation in Buildings D2 – Regulations and Guidelines*, Helsinki, Government Printing Centre.

Nordic Committee on Building Regulations (NKB) (1981) *Indoor Climate*, Stockholm, Nordic Committee on Building Regulations (NKB Report No 41).

Reinikainen, L.M. and Jaakkola, J.J.K. (1993) "The effect of room temperature on symptoms and perceived indoor air quality in office workers. A six week longitudinal study". In: Jaakkola, J.J.K., Ilmarinen, R. and Seppänen, O. (ed.) *Proceedings of Indoor Air '93*, Helsinki, Vol. 1, pp. 47–52.

Reinikainen, L.M., Jaakkola, J.J.K. and Seppänen, O. (1992) "The effect of air humidification on the symptoms and perception of indoor air quality in office workers: A six-period cross-over trial", *Archives of Environmental Health*, 47, 8–16.

SAS/STAT User's Guide (1988) Cary, NC, SAS Institute Inc. (Release 6.03 edition).

Schiller, G.E., Arens, E.A., Bauman, F.S., Benton, C., Fountain, M., Doherty, T. and Craik, K. (1988) "A field study of thermal environment and comfort in office buildings", *ASHRAE Transactions*, **94**, Pt 2, 280–308.

Schiller, G.E. (1990) "A comparison of measured and predicted comfort in office buildings", *ASHRAE Transactions,* **96,** Pt 1, 609–623.

Seppänen, O. and Jaakkola, J.J.K. (1989) "Factors that may affect the results of indoor air quality studies in large office buildings". In: Nagda, N.L. and Harper, J.P. (eds) *Design and Protocol for Monitoring Indoor Air Quality*, Philadelphia, American Society for Testing and Materials, pp. 51–62 (ASTM STP 1002).