Distribution of Thermal Sensation Votes in Offices used to Model Annual Mental Performance Decrements

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SUMMARY

This paper presents the development of distribution models of office employee's thermal sensation and an introduction to a methodology how to integrate the fact that humans perceive temperature differently with the effects of temperature on mental performance. Two different distribution models have been developed; one for occupants in mechanically ventilated buildings and one for occupants in naturally ventilated buildings. The results show that there is a significantly difference ($P<0.05$) in how people assess the indoor thermal environment depending on ventilation principle. Thus when calculating the effects of temperature on occupants' mental performance it is important not only to take the individual differences into consideration between humans, but also building ventilation principle.

INTRODUCTION

Effects on employee performance of different indoor climate parameters have received considerable attention during recent years [1, 2, 3, 4]. Several studies have shown an increase in mental performance from 5-10% (in some cases up to 20%) when improving the indoor climate e.g. by increasing the air change rate, provide better temperature control or use better filtration [1, 5, 6, 7]. Based on substantial numbers of field and laboratory studies, Seppänen et al. [2, 3, 8] have suggested models to describe relationships between performance and different indoor climate parameters. Design tools for evaluating the economical implications of investments in indoor environmental quality, which take into account employee productivity, may provide strong arguments to companies to invest in improved indoor environment. Such tools need appropriate relation between indoor environment factors and performance to be functional and convincing.

Development of relationships between indoor climate parameters and mental performance (e.g. an indoor air temperature of 30 °C reduce performance of office workers with 10%) is the first element of a model that can be used for estimating the potential economical gains of an investment in better indoor environment. Two other elements should be included in order to make the model stronger and more precise:

1. Hourly data of the indoor environment
2. Distribution models of the employees in a given environment

Since the indoor climate is normally dynamic (variation over day and season) calculation on an hourly basis during a year may be used as a more representative input to estimate the effects on mental performance of the indoor climate. These hour by hour values of the indoor climate can typically be obtained using computer simulation. Many different building simulation tools to evaluate the indoor climate exit on the market. Using the output from such tools in a performance calculation program, enables easy comparison of different building designs and their effects on performance.

Even when exposed to a uniform indoor environment (e.g. in well controlled climate chambers) humans perceive the indoor environment differently e.g. [9]. It is thus likely that occupant performance will be affected differently in different individuals, e.g. as a consequence of individuals having a different thermal sensation even though their exposed to only one (uniform) temperature.

Using distribution models of the employees' perception of the indoor environment allows differences between individuals to be taken into account. People do not sense the indoor climate the same way, some find it draughty, too cold, and too stuffy while others find the same conditions comfortable. Knowledge of the distribution of sensation of different indoor climate parameters may be a step to better assess indoor climate effects on performance.

Temperature is one of the most investigated parameters and it is one of the indoor climate parameters that cause most complaints [10]. Figure 1 shows schematically, the different steps of the methodology on how to evaluate effects on mental performance of temperature. Step 1, first the air temperature needs to be calculated on an hourly basis using building simulation tools. Step 2, air temperature is used with other factors (clothing insulation, relative humidity, air velocity, ventilation system etc.) to evaluate mean thermal sensation distribution of the employees. Step 3, the corresponding perceived temperature for each level of thermal sensation in the distribution is calculated. Step 4, mental performance decrement can be calculated on an hourly basis during a year.

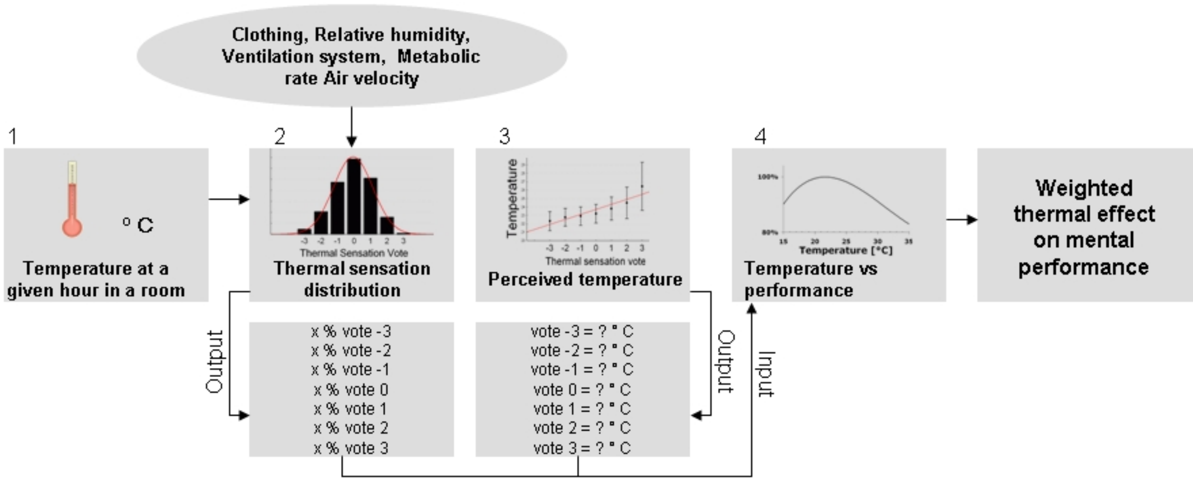


Figure 1. Methodology of calculating mental performance loss due to the effects of air temperature

In this paper distributions of thermal sensation votes will be used to assess the resulting distribution of perceive temperature and the corresponding weighting factors. The distribution will be based on data from ASHRAE RP-884 Adaptive Model Project [11]. The database contains corresponding set of indoor climate measurements and thermal sensation votes from thousands of office employees around the world, occupying hundreds of mechanically and naturally ventilated buildings. The distribution will be based on responses from building occupants, rather than subjects in laboratories, to reflect better the non-uniform condition that occur in buildings in practice. This distribution will be used as input to model effects mental performance effects of the thermal environment during a full year.

METHODS

Taking into consideration that individuals respond differently, even when exposed to the same environment, it is likely that at 22 °C some occupants will feel warm or neutral while others may feel cool or cold. Fanger [9] observed a distribution of thermal responses from sensation votes under different air temperatures. This distribution was based on votes cast by human subjects during exposure to uniform conditions in laboratory environments. During the exposure, subjects were asked to vote on the 7-point ASHRAE scale ranging from Cold to Hot (see Figure 2).

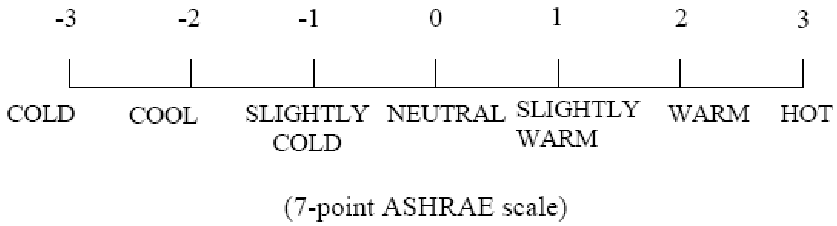


Figure 2. ASHRAE 7-point Thermal Comfort scale

Instead of using climate chamber data we choose to investigate data from field studies. These studies used the scale in Figure 2, but in real office environments. Table 1 shows an overview of the data used in this paper. Data has been divided into two main categories: Mechanically ventilated and naturally ventilated (NV) buildings.

Table 1. Overview of investigated data

Ventilation system	**Number of subjects**	**Buildings**
Mechanical	8119	100
Natural	4679	24
Total	12798	124

The data consists of information from over 12700 occupants in 124 different buildings. Subjective assessments of the thermal conditions and physical indoor climate parameters (e.g. air temperature, air velocity, relative humidity) have been monitored. The buildings were primarily office buildings. Only data with occupant activity levels below 1.3 Met and clothing insulation values below 1.1 clo was included. The data from ASHRAE RP-884 Adaptive Model Project was classified in three broad classes: Class I, Class II and Class III. Class III field studies were based on simple measurements of temperature and simple questionnaires, and these data where excluded from the present investigation. Only data from investigations which were classified as Class I or Class II was included in the present analysis. Class II data includes data where all indoor physical environmental variables necessary for the calculation of PMV/PDD indices were made at the same time and place as the thermal questionnaires were administered. Class I data consists of data of same type as Class II data, but the measurements and procedures were in 100% compliance with ASHRAE Standard 55 (1992) and ISO 7730 (1984) (e.g. measurements in three heights, measurement of turbulence intensity etc.) The statistical program Statistica 7.1 was used for data management and statistical calculations.

For each one-degree interval of indoor air temperature from 20-30°C measured in the mechanically ventilated buildings and from 20-33°C in naturally ventilated buildings, the count of corresponding thermal sensation votes in one scale-unit intervals from -3 to +3 was recorded and used to describe the distribution.

RESULTS

Table 2 and 3 show the distribution of thermal sensation votes for occupants in mechanically and naturally ventilated buildings. The tables show the number of occupants who were exposed to a certain air temperature and the corresponding percent of occupants who voted a certain category on the 7-point ASHRAE thermal comfort scale.

Table 2. Distribution of Thermal Sensation Votes (%) in mechanically ventilated buildings

°C	N	-3	-2	-1	0	1	2	3
20	109	9%	27%	34%	24%	6%	1%	-
21	374	8%	14%	30%	32%	11%	4%	1%
22	1590	7%	16%	32%	30%	12%	3%	-
23	2712	3%	11%	28%	35%	19%	4%	-
24	2093	2%	10%	23%	33%	24%	7%	-
25	752	-	4%	16%	30%	35%	14%	2%
26	234	-	-	5%	24%	44%	22%	5%
27	113	-	2%	5%	8%	39%	31%	15%
28	32	-	-	-	3%	22%	41%	34%
29	15	-	-	-	-	53%	27%	20%
30	43	-	-	-	-	16%	44%	40%

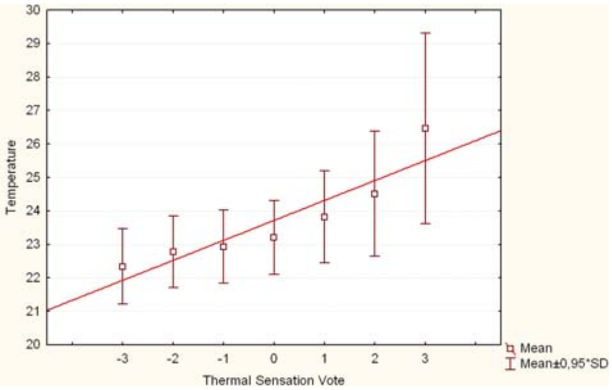
Table 3. Distribution of Thermal Sensation Votes (%) in naturally ventilated buildings

°C	N	-3	-2	-1	0	1	2	3
20	37	3%	27%	32%	11%	19%	8%	-
21	129	7%	16%	23%	20%	17%	15%	2%
22	212	2%	10%	24%	28%	20%	14%	2%
23	308	2%	7%	19%	32%	24%	13%	2%
24	243	2%	3%	15%	36%	26%	14%	4%
25	301	3%	13%	24%	23%	24%	11%	3%
26	531	2%	13%	26%	25%	25%	9%	1%
27	626	1%	7%	24%	30%	25%	12%	1%
28	390	-	3%	16%	28%	30%	19%	4%
29	434	-	-	6%	35%	40%	15%	2%
30	544	-	1%	3%	29%	42%	21%	4%
31	511	-	1%	3%	27%	42%	23%	4%
32	245	-	-	3%	22%	46%	25%	4%
33	88	-	-	1%	17%	61%	18%	2%

Table 2 and 3 show that at e.g. 21 °C, 24 °C and 27 °C there is a difference in the distribution of thermal sensation votes between occupants in naturally and mechanically ventilated buildings. This difference is significantly ($p<0.05$) for all temperatures between 20-30 °C, a finding also described in [11]. It is evident that when temperature increases, the thermal sensation of the occupants also increases in both types of buildings, but at the indoor temperature 21 °C in NV buildings, 40% of the occupants was dissatisfied (voting -3,-2, +2 or +3 on the 7-point scale) compared to only 27% dissatisfied occupants in mechanically ventilated buildings. At 24 °C the number of dissatisfied is similar comparing the two different ventilation principles, 23% and 20% for NV and mechanically ventilated buildings, respectively. In warm indoor environments at 27 °C in mechanically ventilated buildings occupants are more dissatisfied than occupants in NV buildings, 48% dissatisfied compared to 21% dissatisfied, which corresponds with the rationale behind the adaptive model of thermal comfort [11].

Perceived air temperature

This data set allows establishment of a relationship between thermal sensation votes and temperature. This can be used to estimate occupants' perceived air temperature corresponding with a given vote on the thermal sensation scale. Figure 3 shows this relationship in mechanically and naturally ventilated buildings, respectively.



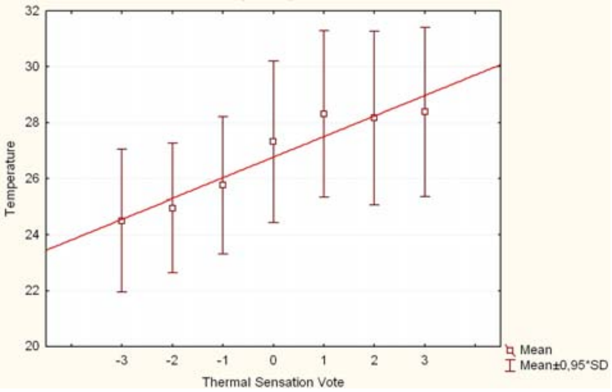


Figure 3. Relationship between office employees' thermal sensation votes and measured temperature in mechanically ventilated building (left figure) and NV buildings (right figure)

Figure 3 shows the mean temperature measured for each thermal sensation vote and the standard deviation. The mean temperature perceived as neutral (the average temperature measured for occupants who voted 0 on the thermal sensation scale) in mechanically ventilated buildings was 23.2 °C and 27.3 °C in naturally ventilated buildings. A linear regression line is used to describe the relationship between thermal sensation and temperature. E.g. for occupants in mechanically ventilated buildings voting 2 (warm) on the sensation scale the corresponding perceived air temperature will be 24.9 °C.

Table 3 shows an example of the combination of the thermal distribution at 24 °C for occupants in mechanically ventilated buildings and the corresponding perceived air temperature (the point on the regression line from Figure 3).

Table 3. Perceived air temperature for occupants exposed to 24 °C indoor environment

Thermal sensation vote	-3	-2	-1	0	1	2	3
Thermal distribution	2%	10%	23%	33%	24%	7%	-
Perceived air temperature	21,9 °C	22,5 °C	23,1 °C	23,7 °C	24,3 °C	24,9 °C	25,5 °C

From table 3 it is seen that 33% of the occupants in mechanical ventilated buildings who voted 0, may perceive the air temperature as being 23.7 °C, but 7% perceive the temperature as 24.9 °C. When calculating the effects of temperature on mental performance, occupants are affected differently even when exposed to the same temperature, due to the differences in thermal sensation between individuals. When the temperature varies the distribution of thermal sensation changes, thus by calculating this weighted effect of temperature on performance hourly over a year, an expression of the total yearly performance can be estimated.

DISCUSSION

In order to estimate the effects of temperature or other indoor climate parameters on mental performance of office work, the distribution of individual perceptions may be used as input to the calculations. With thermal sensation it is well established that not all people feel neutral at 22 °C, but as seen from this study e.g. 14% of occupants in NV buildings sense 22 °C as “warm”. This could be due to behavioral or psychological differences, a variation that normally occurs between occupants in offices around the world. Over an entire population occupants voting “warm” on the thermal sensation scale, would perceived the indoor air temperature to be 28.2 °C. Thus this is the temperature that will affect the mental performance.

By using a relationship between mental performance and air temperature established in e.g. [2], the distribution of thermal sensation votes and their corresponding perceived air temperature, a weighted effect of temperature on mental performance of office workers can be calculated. Since some occupants will perceive temperatures that differ from the optimal performance point of view, it will not be possible to reach 100% performance for a group of occupants even under thermal conditions that are acceptable to a majority of the occupants.

Future challenges are to integrate hourly temperature output from building simulation programs and a relationship between mental performance and temperature with the developed distribution and perceived temperature in a design decision tool. This tool could make it possible to compare different building designs in relation to investments in improvement of the thermal indoor climate and the corresponding effects on occupants’ mental performance.

CONCLUSION

The distributions developed in this paper can be used for future estimation of the effects of temperature on mental performance. Occupants do not perceive the temperature or other indoor parameters uniformly. The approach suggested in this paper allows individual differences to be accounted for when assessing effects on performance of indoor climate, as it varies during the year.

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