Thermal Comfort in a Naturally Ventilated Office Building in Karlsruhe, Germany – Results of a Survey

Andreas Wagner, Cornelia Moosmann, Thomas Gropp, Elke Gossauer

Division of Building Science, University of Karlsruhe, Englerstr. 7, D – 76131 Karlsruhe, Germany

Corresponding email: andreas.wagner@fbta.uni-karlsruhe.de

SUMMARY

In order to compare measurements and subjective votes on thermal comfort in a non-conditioned indoor environment under German climate conditions, a field survey was carried out in an office and laboratory building in Karlsruhe during July 2005. Over a period of 4 weeks 50 subjects filled in questionnaires twice a day every Tuesday and Thursday and accompanying measurements were carried out at the workplaces. 90% of the votes on thermal sensation proofed the room temperatures to be "just right" or "slightly warm"; these votes cover ranges of more than 5 Kelvin of the operative temperature and also include 7.5% temperatures above 27°C. About 75% of all votes rated the indoor climate neutral or better although the room temperatures showed fluctuations in space (rooms of the building) and time (period of the study).

INTRODUCTION

A field study in a German office building was carried out to address the topic of thermal comfort and accepted indoor temperatures during summer, which is of great importance particularly in naturally ventilated and passively cooled buildings. Several studies (e.g. [1], [2], and [3]) showed that the subjective votes of occupants in naturally ventilated or passively cooled buildings correspond with a temperature band dependent on the outdoor temperature under transient summer conditions. With the introduction of the European "Energy Performance of Buildings Directive" an increasing number of commercial buildings without air-conditioning will be realized in the future. Therefore further knowledge is necessary about the perception and acceptance of a varying indoor thermal environment particularly during summer also taking into account future climate changes. Additionally, more experience with field surveys on thermal comfort has to be gained in comparison with climate chamber experiments.

DESCRIPTION OF THE BUILDING AND EXPERIMENTAL SETTINGS

The field study was carried out in an office and laboratory building situated on the campus of the "Forschungszentrum Karlsruhe", Germany. The building has a net area of approximately 5,300 m² and includes an older existing part and a new extension built in 2004, both accommodating (mostly smaller) offices as well as laboratories for chemical experiments. All offices in both building parts are ventilated naturally all year whereas the laboratories are ventilated mechanically due to the special requirements for these workspaces.

The new extension building was built as a low energy building comprising features like high heat insulation standards, a passive cooling concept for the offices as well as high daylight availability. Its thermal mass is discharged by night ventilation due to the stack effect in a central staircase, with cold outside air coming into the building through remote-controlled skylight windows in the offices. The older part of the building has suspended ceilings in the offices and less insulation of the building envelope. No passive cooling is used and it was therefore expected that the occupants' comfort perception would reflect the differences of the thermal behaviour of the two building parts.

During the study, which was carried out in July 2005 over a period of 4 weeks, short questionnaires had to be filled in by the participants twice a day every Tuesday and Thursday, resulting in 16 single surveys during the 4 weeks. In the questionnaire all aspects relevant to comfort, like room temperature, air velocity, humidity, air quality and light were addressed. Two slightly different questionnaires were used for the morning and the afternoon survey to gain some specific information related to the expectations about the indoor climate on entering the building and to changes of the indoor climate during the day. All questions had to be answered within a 5-point-scale by the participants. Sections for free comments were also provided.

A total number of 50 subjects who regularly work in the building participated in the whole study with half of them completing 9 or more single surveys (out of 16 in total). The surveys were accompanied by measurements of the relevant thermal comfort parameters during the time the questionnaires were filled in by the subjects. Additionally, the indoor air temperatures and relative humidity were recorded continuously throughout the 4 weeks in those rooms were the survey was carried out. Outdoor climate data for the site were available for the whole period. Further information on the experimental procedure is given in [4].

RESULTS OF QUESTIONNAIRES AND MEASUREMENTS

The study was carried out in a period which represented a typical but not very hot summer month for Karlsruhe with temperature maxima above 30°C on five days and distinct temperature differences between day and night on most of the days. The variations between single days and between shorter periods of similar climate conditions were strong enough to expect some affect on the subjects' votes. Radiation, temperature and humidity data are given in [4].

The resulting indoor temperatures for this period are given in figure 1. The room temperatures lie in an acceptable range for most of the time; only the temperatures in the rooms on the second floor of the old part of the building exceed 26°C for almost 50% of the whole period. The old part of the building shows a stratification of temperatures between the single floors. In the new part of the building, temperature differences between the floors are much smaller. All floors here show temperatures similar to the first floor of the old part. The effect of night ventilation is very different, both between the two parts of the building and between floors. Temperatures in the new extension did not often decrease below 23°C, even if the outdoor temperature was below 20°C at the same time. The second floor of the old building part without night ventilation hardly showed any cooling effect during the nights whereas the ground floor had the same characteristic as the new extension.

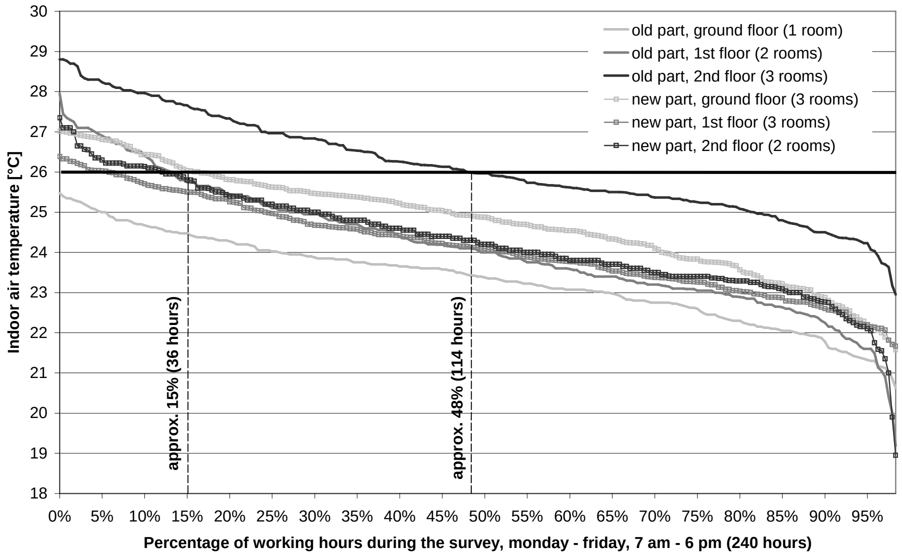

Figure 1. Indoor air temperatures in the rooms where the surveys were carried out. The bold black line at 26°C corresponds to the temperature limit of the German workplace regulations.

In figure 2 the votes for thermal sensation are given subject to the operative indoor temperature. The votes for "just right" and "slightly warm" represent 90% of all votes. They cover ranges in operative temperatures of more than 5 Kelvin and also include temperatures above 27°C. The votes for "very warm" (7% of all votes) cover a range from 25 to 30°C.

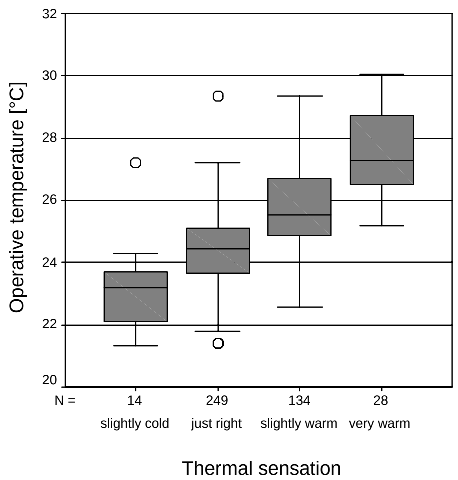

Figure 2. Box plot of votes of thermal sensation against operative temperature in the rooms. The lines in the boxes represent the median values, the grey boxes cover the mean 50% of the values and the thin lines show the whole range of all values. The small circles indicate outlines. The analysis of variance shows a significant correlation between operative temperature and votes of thermal sensation ($\alpha=0.05$, $p<0.001$, N=425).

Further analysis shows that the occupants accept higher temperatures in the upper floors – the median of the vote "just right" is at 24°C on the ground floor and 25°C on the second floor (see figure 3). This is also true for differences between the old and the new part of the building where the mean votes of "slightly warm" and "very warm" also differ significantly by up to 1.8 Kelvin ($\alpha=0.05$, $p=0.001$, N=133 for "slightly warm" and N=27 for "very warm").

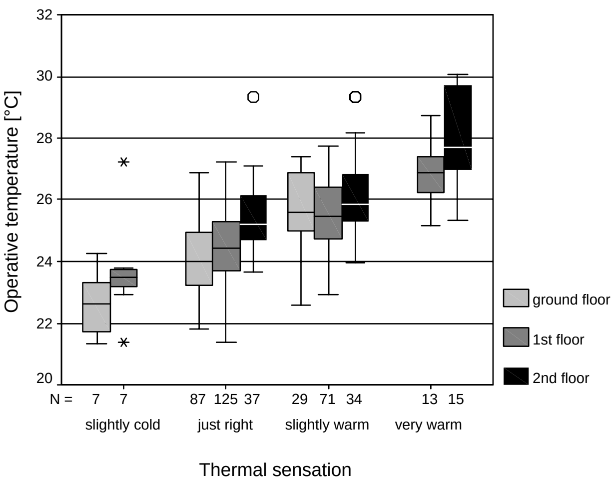

Figure 3. Box plot of votes of thermal sensation against operative temperature for the different floors of the building. The lines in the boxes represent the median values, the grey boxes cover the mean 50% of the values and the thin lines show the whole range of all values. The small circles indicate outlines. The analysis of variance shows a significant difference between the measured temperatures that are voted "just right" for the different floors ($\alpha=0.05$, $p<0.001$, N=249).

An increase of the indoor temperature during the day was perceived by approximately 66% of the participants which relates to the character of a free-floating building. Figure 4 shows that temperature ranges for thermal sensation votes are different in the mornings (8 a.m. to 10 p.m.) and in the afternoons (2 p.m. to 4 p.m.). In the afternoons, temperatures are judged "cooler". The median temperature of the vote "slightly warm" is 24.9°C in the mornings. This temperature is below the median value of "just right" in the afternoon (25.2°C). The median temperatures of the same votes are about 1.3°C higher in the afternoon.

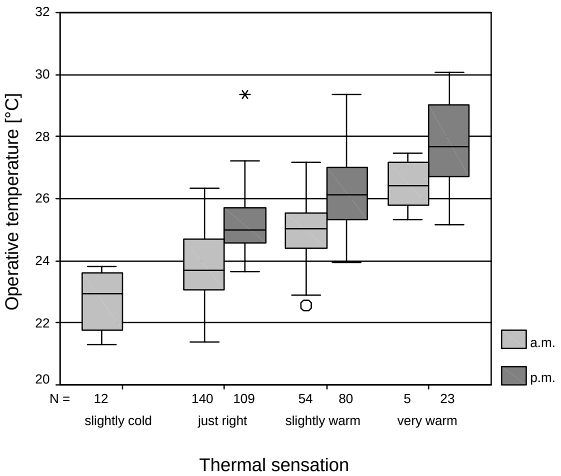

Figure 4. Box plot of votes of thermal sensation against operative temperature in the rooms in the morning and in the afternoon. The light grey boxes cover the mean 50% of the values in the mornings, and the dark grey boxes show the votes in the afternoons. The group "slightly cold" in the afternoon (n=2) has been excluded in the box plot. The analysis of variance shows a significant difference between votes in the mornings and in the afternoons ($\alpha=0.05$, $p<0.001$, N=425).

Analysis of the clo-values showed that most persons did not change their clothes on the days the surveys were carried out. The results also showed that the occupants used to open the windows more often in the morning (with cooler outdoor temperatures) compared to the afternoon but there is no indication from the measurements that the indoor temperature was influenced strongly. However, a rather large number of persons did not stay in the room between the two surveys but worked in a laboratory. They re-entered the office approximately 15 to 30 minutes before the afternoon survey.

Regarding the whole survey period the temperature range which is judged as "just right" varies significantly ($\alpha=0.05$, $p<0.001$, $N=249$). Figure 5 shows that the ranges of July 5th, 7th and 21st equal each other, 12th and 19th are similar and July 14th and 28th show the highest temperature ranges voted as "just right". In the mornings, the lowest median temperature voted "just right" is 23.2 °C on July 21st; the highest median temperature is 25.2 °C on July 28th. In the afternoons, the lowest median value is 24.2 °C on July 7th and the highest value is 27.2 on July 28th. The maximum differences in median temperatures for the vote "just right" are 3 K in the mornings and 3 K in the afternoons with 2 K higher median values in the afternoons. It has to be taken into account that the clo-values change significantly throughout the period. People dress themselves according to the outdoor temperature, as can be seen in figure 5.

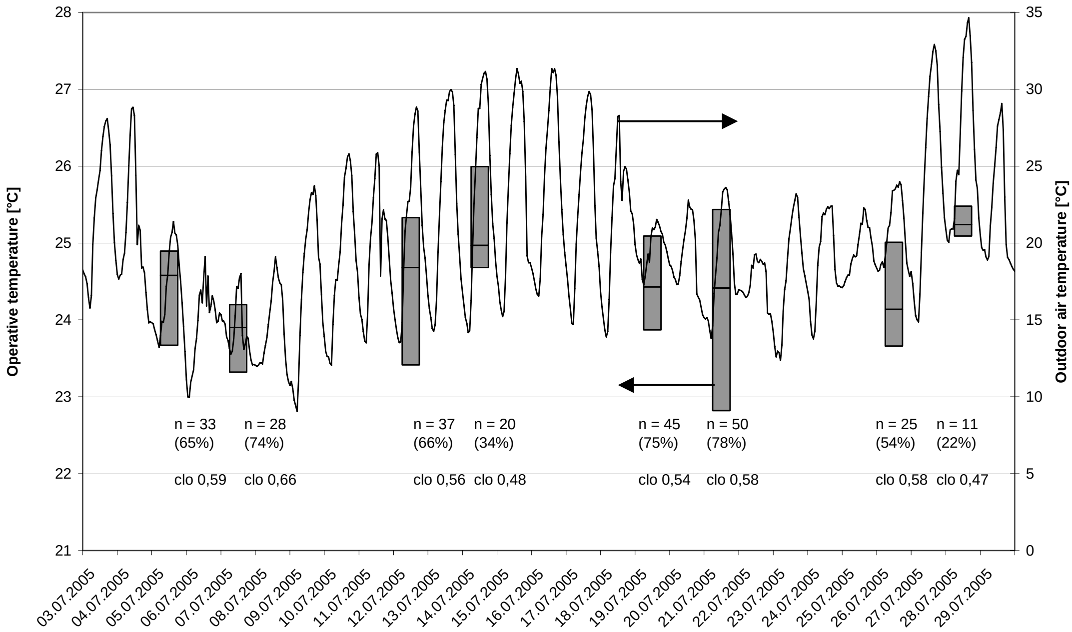

Figure 5. Outdoor air temperature during the whole study and operative indoor temperatures which were judged "just right"; the lines in the boxes represent the median values and the grey boxes cover the mean 50% of the values.

On all eight days most the participants (76%) expected the outdoor temperature to be as it was after they left their homes in the morning. No rules could be found for those votes where expectations were not fulfilled. The results for expectations concerning the indoor temperature before entering the workspace are similar: again, the majority (72%) expected the indoor temperature to be as it was on all days. If the expectations were not met the votes were mainly "slightly warmer" or "much warmer" (84%). Some of these votes can be explained by the cool outdoor temperature on that day or by unexpected changes in temperature. However, the number of votes / subjects is too small to obtain statistically significant correlations.

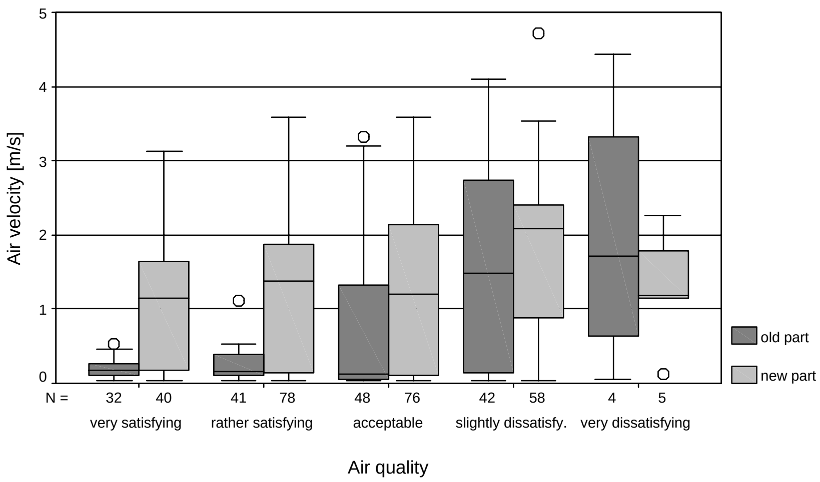

Figure 6. Box plot of votes of the perception of air quality against air velocity in both parts of the building. The dark grey boxes represent the values in the old part of the building, and the light grey boxes show the votes in the new part. The perception of air quality is not significantly different for both parts, air velocity differs significantly ($\alpha=0.05$, $p<0.001$, N=427). The correlation between air quality and air velocity is significant for the old part ($\alpha=0.05$, $p<0.001$, N=167) but not for the new part ($\alpha=0.05$, $p=0.006$, N=257).

With respect to perceived air movement the occupants wished to have higher air velocities with a thermal sensation of "slightly warm" or "warm". Subjects demanding stronger air movements felt no or only a slight movement (chi^2: $\alpha=0.05$, $p<0.001$, N=211). The evaluation of air quality also correlated significantly with the operative temperatures (analysis of variance: $\alpha=0.05$, $p<0.001$, N=424); negative votes were mostly "stuffy" and "sticky" coinciding with higher room temperatures. In figure 6 it can be seen that the air velocities increase with worse votes on air quality in the old part of the building. It seems that the occupants try to compensate the situation – bad air quality mostly as a synonym for high temperatures – by ventilating their offices.

The votes on thermal sensation, indoor air quality and overall indoor climate correlate with each other with a high level of significance. The self-reported productivity also corresponds significantly with these three parameters, and to the reported feeling (bad/well, tired/alert, hard/easy to concentrate on the work, depressed/in a positive mood). Figure 7 shows that only 9 votes out of 425 evaluated the (overall) indoor climate as "very unsatisfying" and 95 votes as "slightly unsatisfying". These votes correspond to a majority of votes of "very warm" and "slightly warm" for the thermal sensation. The neutral and positive votes on indoor climate coincide well with a large acceptance of the indoor temperature.

DISCUSSION OF THE RESULTS AND CONCLUSIONS

The methodology of the survey proofed to be practicable but very intensive for both the subjects and the researchers. After 4 weeks the motivation of the participants seemed to decrease which gives a hint for limiting extensive field studies to similar periods. The acceptance of the surveys was very high, probably because the participants were mostly scientists as well. The study in this particular building had two major shortcomings:

- the participants were not available for all surveys resulting in disparate samples for the single surveys;

- the participants did not work in their offices for the whole day and therefore experienced different room climates (particularly the climate in the mechanically ventilated laboratories).

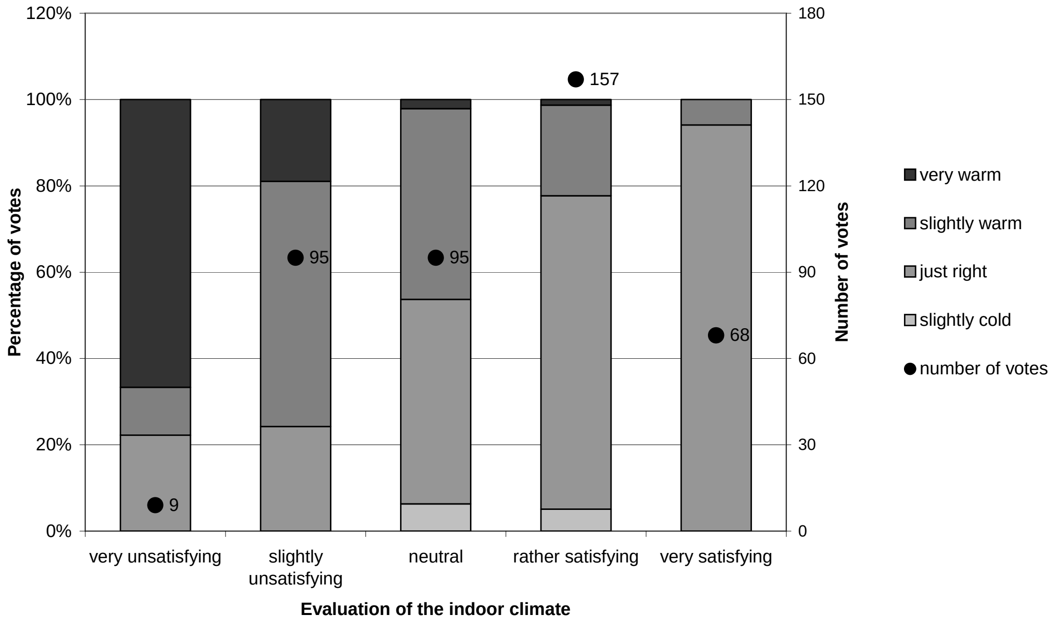

Figure 7. Relationship between votes of thermal sensation and overall satisfaction with the indoor climate

The results of the study show that a positive perception of thermal comfort is not limited by a sharp limit of the indoor temperature. Even the votes "just right" on the thermal sensation include operative temperatures higher than 27°C. About 75% of all votes rated the indoor climate neutral or better although the room temperatures showed fluctuations in space (rooms of the building) and time (period of the study).

On the other hand, the temperature levels in most monitored rooms were rather moderate with only 15% of the working hours of the whole period (240 hours) showing temperatures above 26°C. This proofs the good design of the building, particularly of the new part, in terms of passive cooling. The exception was the second floor of the old part of the building with 114 working hours above 26°C but below 29°C. In this part of the building, 50% of the indoor climate votes are negative, which is significantly above average (25%).

Regarding the fluctuations of temperatures and coinciding thermal sensations in different parts of the building it was found that occupants seem to accept higher temperatures in their offices. Their positive votes correlate to higher temperatures on the upper floors and in the old part of the building compared to other offices in the building. It was also found that the votes of thermal sensation correlate with the outdoor temperatures. The median temperature ranges of positive votes (e.g. "just right") are higher in the afternoon and on days with higher outdoor air temperatures. These findings are in agreement with other results on adaptive thermal comfort (e.g. [1], [2], and [3]).

The study showed that naturally ventilated and passively cooled buildings can be highly appreciated by occupants during summer if they are designed properly in terms of the indoor climate. Positive perceptions of thermal comfort do occur outside the temperature limits set in standards for air conditioned buildings. The study therefore confirms that adaptive comfort models are more suitable to predict the thermal sensation and thermal comfort of occupants, if periods with transient indoor (and outdoor) climate conditions are considered. This is mostly true for summer climate conditions, during which the study had been performed.

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