Thermal Comfort under Summer Climate Conditions – Results from a Survey in an Office Building in Karlsruhe, Germany

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Abstract

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 overall indoor climate neutral or better. The actual votes on thermal sensation do not correspond to predicted mean votes which were calculated with the data measured during the interviews, but a very good agreement can be seen with adaptive comfort models.

Keywords

Thermal comfort, thermal sensation, post occupancy evaluation

Introduction and purpose of the study

The issue of thermal comfort at workplaces gained much importance in Germany since the very hot summer of 2003. This is not only true regarding different passive and active (technical) solutions for appropriate indoor environment conditioning but also with respect to current standards and workplace regulations. Particularly with the introduction of the new European directive on buildings' energy performance, conventional cooling or air-conditioning concepts might fail in the future in terms of energy consumption targets and on the other hand passive cooling might not meet the current limits for the indoor temperature.

These temperature limits have been discussed controversially in Germany, particularly in connection with non-conditioned indoor environments for which standards and regulations are not consistent. A (hopefully provisional) result is that the maximum indoor temperature was fixed to 26°C[1] by jurisdiction. This result is unsatisfactory as several studies in comfort research (i.e. [1], [2] and [3]) show that subjective votes of users in naturally ventilated or passively cooled buildings with transient summer conditions do not correspond with an indoor temperature limit but with a temperature band subject to the outdoor temperature.

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[1] up to an outdoor temperature of 32°C; above that a difference of 6 Kelvin has to be maintained

The purpose of the field survey described in this paper was therefore

- to compare measurements and votes on thermal sensation and thermal comfort in a non-conditioned indoor environment under German climate conditions,
- to compare these results with different international approaches – especially to adaptive models being proposed and already used in other countries,
- to gain experience with field surveys on thermal comfort in order to promote and carry out further investigations of this kind in addition to climate chamber experiments.

Field survey – building and methodology

The field survey was carried out in the ITC-WGT office and laboratory building situated on the campus of the "Forschungszentrum Karlsruhe", Germany. As shown in figure 1, the building with a net area of approximately 5,300 m² includes an older existing part and a new extension built in 2004, both accommodating (mostly smaller) offices as well as laboratories for chemical experiments. In this study, 14 offices face north, two offices have north and south windows, and two offices face south. All offices in both building parts are ventilated naturally all over the year whereas the laboratories are ventilated mechanically due to special requirements for these workspaces.

The new extension building has been realized as a low energy building comprising features like a high heat insulation standard, a passive cooling concept for the offices as well as high daylight availability. Passive cooling is accomplished by glazing with a high selectivity, an external shading system to reduce solar loads during summer and concrete ceilings without suspension which provide mass storage. This thermal mass is discharged by night ventilation due to the stack effect in the central staircase, with cold outside air coming into the building through remote-controlled skylights in the offices.

Figure 1: View of the building from north (right: existing part, left: new extension) and views of two different offices (top: existing part, bottom: new extension)

Compared to an air-conditioned building, no (electric) energy is needed for cooling the offices in the new ITC-WGT extension which results in a low primary energy consumption. The indoor climate is subject to the outdoor climate, the user behaviour and the settings of the controls for night ventilation. The older part of the building shows suspended ceilings in the offices and a lower quality of the building envelope. No passive cooling is applied and it was therefore expected that the users' comfort perception would represent the differences of the thermal behaviour of the two building parts.

During the field survey 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 "interviews" during the 4 weeks. In the questionnaire all relevant aspects concerning 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 interview 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 provided as well.

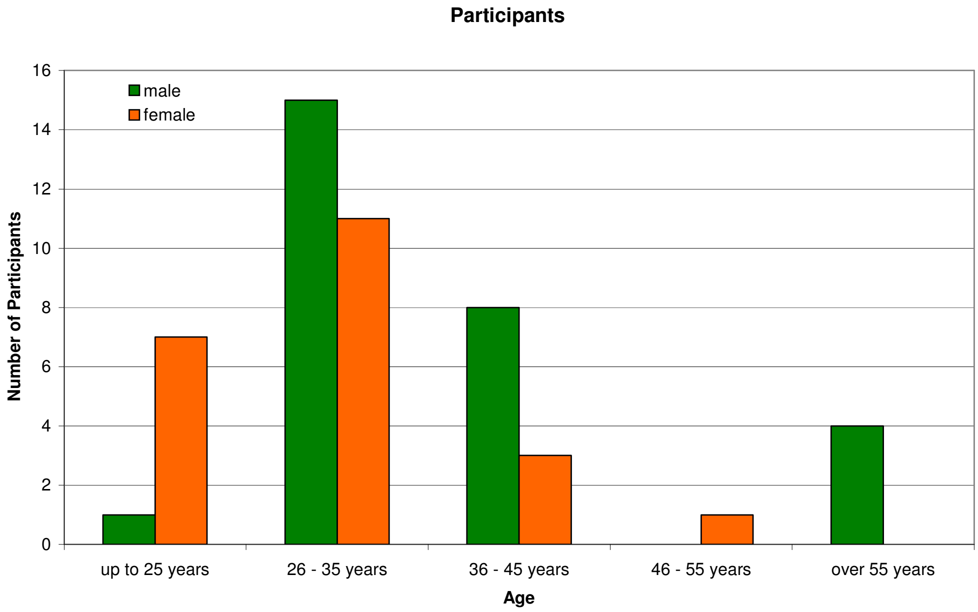

Figure 2: Distribution of age and sex of the participants

A total number of 50 subjects who regularly work in the building participated in the whole survey with half of them participating in 9 and more interviews (out of 16). The mean participation rate was 8.5 for all subjects, 427 interviews could be realised in total. Figure 2 shows the distribution of the participants related to age and sex. Most of the subjects had to work in the laboratories frequently so that they did not stay in the offices for the whole day. However they were asked to return to the offices at least 15 minutes before the interviews. The met values determined with the questionnaire ranged from 1.0 to 3.5 with 13% of all values below 1.2 for office work and 18% of all values above 1.6 for laboratory work[2]. The clo values determined with the questionnaire ranged from 0.33 to

[2] met values according to DIN EN ISO 7730:1995, annex A, table A.1

0.97 with 25% of all values below 0.5 for light summer clothes and 3% of all values above 0.75 for office clothing[3].

The interviews were accompanied by measurements of the relevant thermal comfort parameters (using Innova AirTech Instruments equipment) 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 also available for the whole period.

The data were analysed using mainly two statistical methods. For categorical variables the chi²-test was used and for metric data the analysis of variance was applied with a level of significance of 0.05.

Results of questionnaires and measurements

Figure 3 shows the outdoor conditions during the survey. They represent 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 reactions in the subjects' votes related to that.

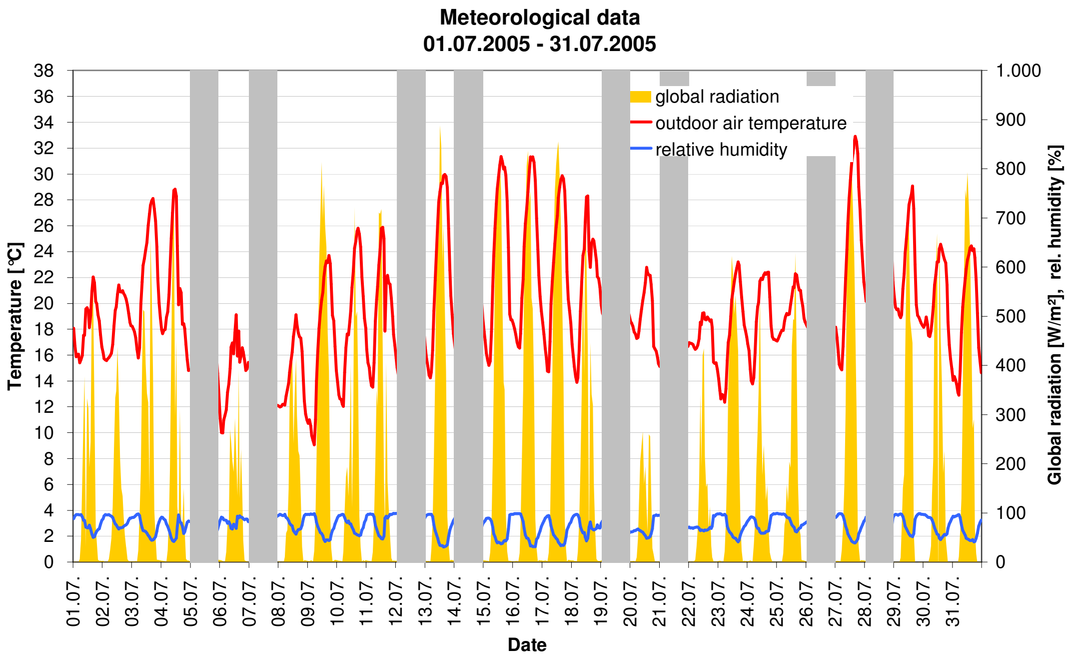

Figure 3: Outdoor climate data during the period of the survey. The grey bars indicate the days on which interviews and measurements have been carried out.

[3] clo values according to DIN EN ISO 7730:1995, annex E, table E.1

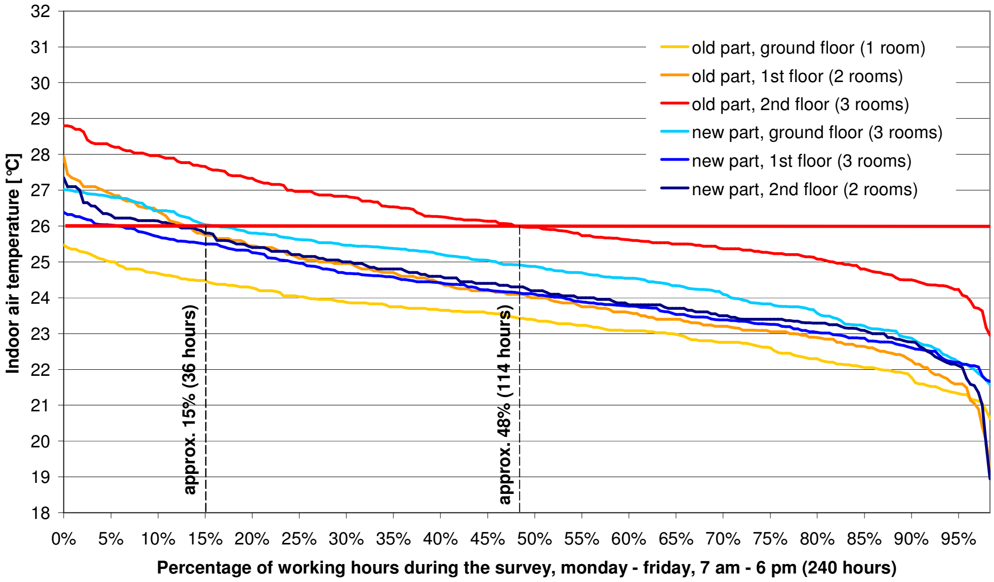

Figure 4: Indoor (air) temperatures in the rooms where the survey was carried out. The red line corresponds to the temperature limit of the German workplace regulations.

The resulting indoor temperatures for this period are given in figure 4. 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 great differences in temperature between the single floors. The room on the ground floor shows the lowest temperatures, the temperatures on the first floor are 0.8 °C higher in average and the temperatures on the top floor are even 2.8 °C higher in average. 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 pronounced differently strong between the two parts of the building and the single floors. Temperatures in the new extension often did not decrease below 23°C with outdoor temperatures far below 20°C. 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.

In figure 5 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 of more than 5 Kelvin of the operative temperature and also include temperatures above 27°C. The votes for "very warm" (7% of all votes) cover a range from 25 to 30°C. Other results reveal a dependency between the votes on thermal sensation and the (actual) outdoor temperatures which indicates the character of a free-floating building. An increase of the indoor temperature during the day was perceived by approximately 66% of the participants. Figure 6 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.

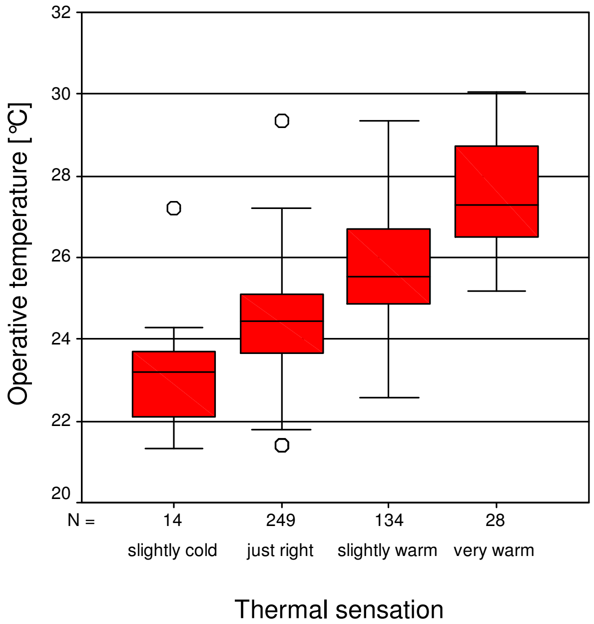

Figure 5: Box plot of votes on thermal sensation subject to the operative temperature in the rooms. The lines in the boxes represent the median values, the red boxes cover the mean 50% of the values and the thin lines show the whole range of all values. The small circles indicate mavericks. The analysis of variance shows a significant correlation between operative temperature and votes on thermal sensation (α=0.05, p<0.001, N=425).

On all 8 days most the participants (76%) expected the outdoor temperature after leaving home in the morning as it was. 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 also give a diffuse picture. Again, the majority (72%) expected the indoor temperature 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 with unexpected changes in temperature. However, the number of votes / subjects is too small to obtain statistically significant correlations.

The votes on humidity are rather scattered; a correlation can be found with the absolute water content of the indoor air which was above 11.5 g/$kg_{dry\ air}$ for 75% of the measured period (mean value: 13.4 g/ $kg_{dry\ air}$). The median values of "slightly/very dry" (13.0/12.0 g/ $kg_{dry\ air}$) are significantly lower than the median values of "slightly/very humid" (14.3/15.3 g/ $kg_{dry\ air}$) when tested with the analysis of variance (α=0.05, p<0.001, N=427). The perception of humidity at times when the room temperature was evaluated "slightly warm" or "very warm" was more or less indifferent ("slightly/very dry" or "slightly/very humid").

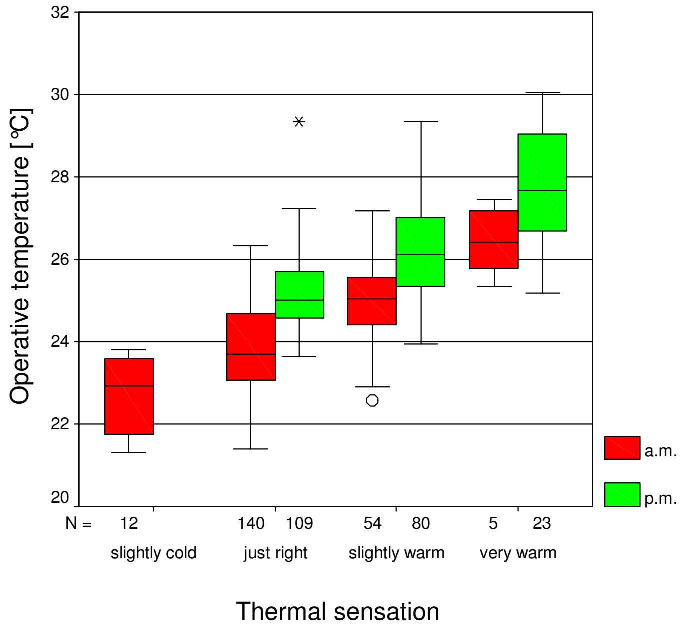

Figure 6: Box plot of votes on thermal sensation subject to the operative temperature in the rooms. The red boxes cover the mean 50% of the values in the mornings, and the green boxes show the votes in the afternoons. The group "slightly cold" in the afternoon (n=2) has been excluded in the box plot. The analysis of variance shows a significant difference between votes in the mornings and in the afternoons (α=0.05, p<0.001, N=425).

The perception of air movement shows a broad range of measured air velocities with only small differences for the single classes of votes. This can probably be explained with the measurements themselves. They were done at one point in a room regardless how many persons were working in that room. The most (and strongest) sensations have been reported for the neck (63% of all sensations), followed by the lower legs (18%). Subjects demanding stronger air movements felt no or only a slight movement (chi^2: α=0.05, p<0.001, N=211). This is more often the case with the thermal sensations "slightly warm" or "very warm".

The air quality was generally evaluated positive with no significant differences in the two parts of the buildings or specific rooms. Negative votes were mostly "stuffy" and "sticky" coinciding with higher room temperatures (significant correlation of perceived indoor air quality and operative temperatures, analysis of variance: α=0.05, p<0.001, N=424).

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.

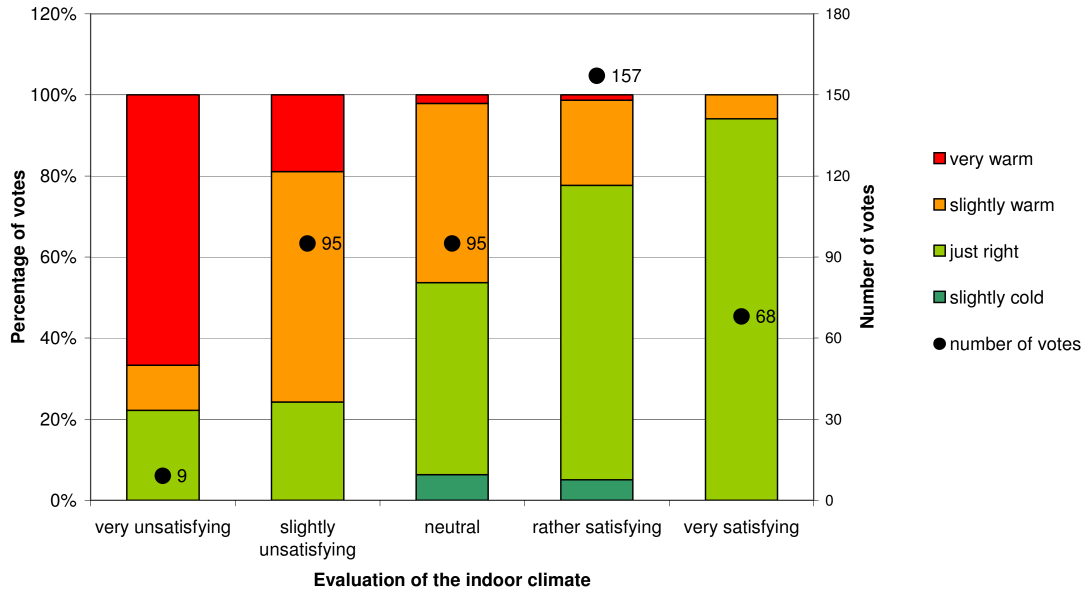

Figure 7: Relation between votes on thermal sensation and satisfaction with indoor climate

The votes on thermal sensation, indoor air quality and overall indoor climate correspond to each other with high significance. The self-reported productivity also corresponds significantly to these three parameters, and to the reported feeling (bad/well, tired/alert, hard/easy to concentrate on the work, depressed/in a positive mood).

The actual votes on thermal sensation do not correspond significantly to predicted mean votes which were calculated with the data measured during the interviews (see figure 8). The range of PMVs is very wide and only changes very slightly dependent on the class of the subjective votes ("just right", "slightly warm" or "very warm"). Surprisingly the PMVs also include negative values indicating a cool or even cold indoor environment.

The temperature range which is judged as "just right" varies significantly ($\alpha=0.05$, $p<0.001$, $N=249$). Figure 9 sows 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.

Discussion and Conclusions

The methodology of the survey proofed to be practicable. The parallel proceeding of two scientists of the University of Karlsruhe guaranteed that the "interviews" and measurements in all 18 rooms could be carried out within approximately 2 hours (15 minutes per room). Therefore two sets of interviews per day were possible with enough time in between. The handing out and direct collecting of paper questionnaires resulted in a return rate of 100% although the data processing caused a higher workload compared to a web-based survey. It was also time-consuming but worthwhile to determine the clo- and met-values individually because they deviated from standard values given in the literature.

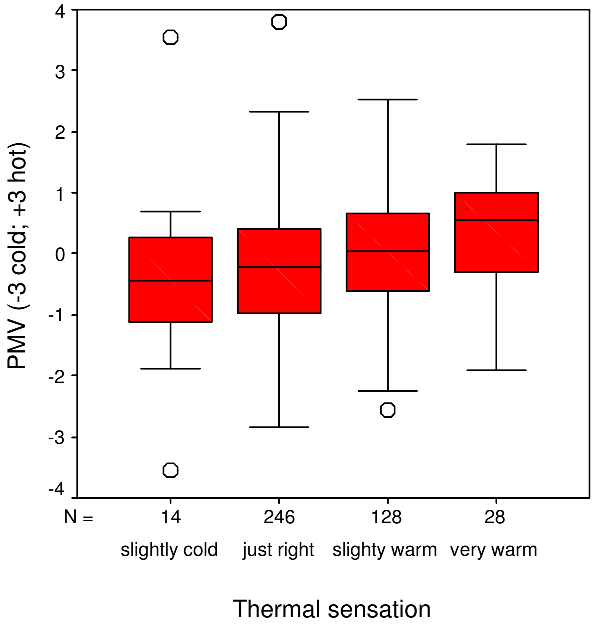

Figure 8: Comparison of votes on thermal sensation and predicted mean votes according to ISO 7730. The lines in the boxes represent the median values, the red boxes cover the mean 50% of the values and the thin lines show the whole range of all values. The small circles indicate mavericks.

The survey in this particular building had two major shortcomings:

- the participants were not available for all interviews resulting in disparate samples for the single interviews;
- 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).

After 4 weeks the motivation of the participants seemed to decrease which gives a hint for limiting extensive field surveys to similar periods. The acceptance of the survey was very high, probably because the participants were mostly scientists as well.

The results of the survey show that a positive perception of thermal comfort is not limited by a sharp limit of the room temperature of 26°C. 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 survey).

On the other hand, the temperature levels in most rooms were rather moderate with only 15% of the working hours of the whole period (240 hours) showing temperatures above 26°C. The exception was the second floor of the older 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%).

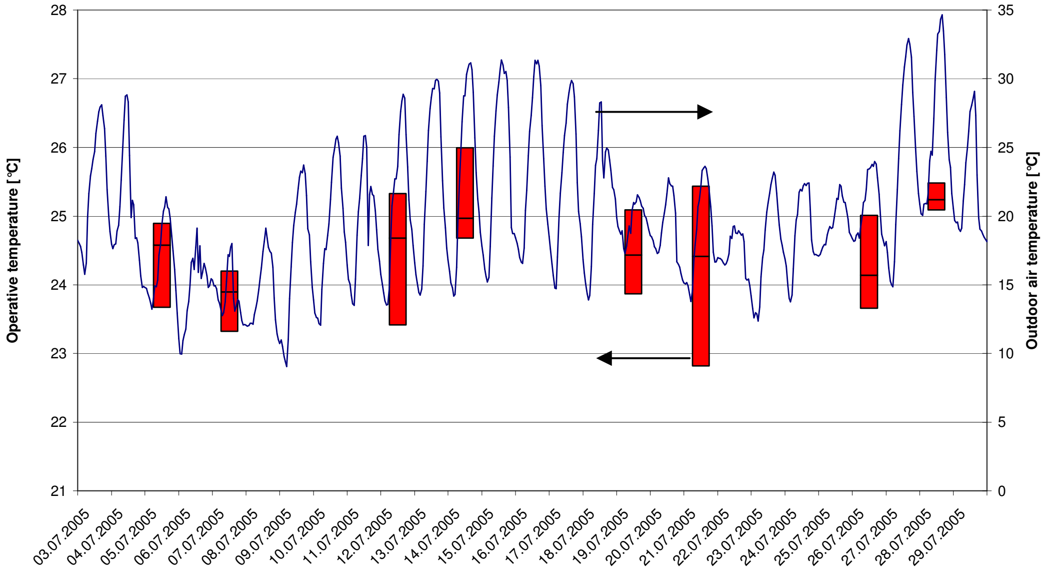

Figure 9: Outdoor air temperature during the survey and operative indoor temperatures which were judged "just right"; the lines in the boxes represent the median values and the red boxes cover the mean 50% of the values.

The deviation of the actual votes on thermal sensation in this survey from predicted mean votes might be due to transient conditions in the free-floating building which cannot be reproduced by the PMV model. As the PMV strongly depends on the air velocity the differences in the results can also be caused by the experimental set-up. The air velocity was measured at one point in a room and particularly in larger offices this measurement might not represent the actual velocities and the resulting perception of air movement in the direct surroundings of the subjects.

It was found that the votes on thermal sensation correlate with the (actual) 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. This is in agreement with other research results. It was therefore examined to which extend the results of this survey fit into different adaptive models. Whereas the fit with the German standard DIN 1946 is rather poor, there is a highly significant correspondence of the comfort votes with the Dutch model [3] and above all with the ASHRAE model [1]. This study can therefore confirm that adaptive comfort models better predict the thermal sensation and that standards used in Germany used at the moment should be revised.

It is planned to continue this work with further surveys during the next years in buildings which take part in the German funding programme ENOB. These buildings are best practice examples in terms of high energy efficiency and mostly rely on passive cooling principles for indoor environment conditioning.

References

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