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Thermal comfort and workplace occupant satisfaction—Results of field studies in German low energy office buildings

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Abstract

The issues of comfort and workspace quality in buildings have gained much importance with the European ‘‘Energy Performance of Buildings Directive’’ of 2001. New energy efficient building concepts and technologies require a revision of comfort standards, which were developed for air-conditioned buildings only. Particularly, the question of recommendable upper indoor temperature limits needs further investigation. In addition, a broader approach to occupant satisfaction in buildings is necessary with respect to overall building performance.

The results of a 4-week summer field study on thermal comfort with 50 subjects in a naturally ventilated office building in Karlsruhe, Germany, show that thermal sensation votes do not correspond to calculated predicted mean votes, but a very good agreement can be seen with adaptive comfort models. The dependence between thermal comfort and the outdoor temperature in naturally ventilated buildings could therefore be confirmed.

A survey on workplace occupant satisfaction in 16 office buildings in Germany revealed that the occupants' control of the indoor climate and moreover the perceived effect of their intervention strongly influence their satisfaction with thermal indoor conditions.

The paper also introduces a method for assessing the building performance by occupant surveys calculating the weighted importance of every satisfaction parameter in relation to the general acceptance of the workplace and then ranking the different satisfaction parameters.

Keywords: Thermal comfort; Thermal sensation; Occupant satisfaction; Satisfaction parameters; Post occupancy evaluation

1. Introduction

The European ‘‘Energy Performance of Buildings Directive’’ has significant impact both on the future design of commercial buildings and their HVAC and lighting systems. As the total primary energy consumption will be limited by new or revised national codes and standards, new building concepts and technologies as well as decentralized energy supply strategies will emerge into the market. A large variety of examples for low energy buildings is already under operation since several years with monitored results and experiences available in different publications and countries.

For example, in Germany a research and demonstration programme was launched in 1995 in order to promote energy efficient commercial buildings. A limit on the total[1] primary energy consumption of 100 kWh/(m^2 a) was postulated as a prerequisite for subsidy. A further condition was that active cooling had to be avoided in normal office spaces. An accompanying research campaign [1] shows that the energy consumption of new office buildings can be reduced to about one third of the average for the German building stock without increasing building construction costs. The targeted primary energy use of 100 kWh/(m^2 a) was reached by most of the 23 participating buildings [2]. Passive cooling proved to be highly effective if heat dissipation in summer is enhanced by night ventilation, slab cooling with vertical ground pipes or earth-to-air heat exchangers.

Despite their benefits of higher energy efficiency, as well as reduced investment and operating costs due to lean technical equipment, these buildings have to meet the occupants' needs for comfort and workspace quality. These factors are not only very important for physiological and psychological reasons, but also play a significant economical role as they strongly influence the occupants' productivity, e.g. ref. [3]. Since personnel costs dominate all other costs related to building

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[1] HVAC + lighting systems, no plug loads.

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operation by two orders of magnitude, appropriate workplace conditions are of utmost importance for the economic success of companies. However, comfort issues do not yet play a major role in the day-to-day operation of commercial buildings, mostly due to a lack of understanding of human comfort and its in situ assessment.

The scientific community on the other hand has been accumulating knowledge on comfort in indoor environments for decades and the most important findings are now the basis of national and international standards, e.g. ref. [4]. Most of the underlying experiments, either performed in the lab or in the field, focused on correlations for thermal comfort criteria [5] or on health issues like the Sick-Building-Syndrome [6]. Fewer publications can be found on the interrelationships between different indoor environmental parameters and the impact of individual satisfaction parameters on the overall satisfaction with workplaces. In recent years, different authors have encouraged field studies, in addition to laboratory experiments, in order to get more reliable information about the actual workplace comfort and the relevant (interacting) parameters, e.g. refs. [7,8].

In this paper, the results of two different field studies in German office buildings are presented, both of which have been carried out to investigate thermal comfort in energy efficient buildings. One study addressed the topic of maximum allowable indoor temperatures during summer, which is of great importance particularly in naturally ventilated and passively cooled buildings. In Germany, this was (and still is) discussed controversially – especially after the very hot summer of 2003 – because the current standards, regulations and recommendations only refer to air-conditioned buildings. Being forced to apply them would lead to restrictions in passive cooling building design. On the other hand, several international studies (e.g. refs. [5,7,9]) show that the subjective votes of occupants in naturally ventilated or passively cooled buildings do not correspond with an indoor temperature limit but with a temperature band dependent on the outdoor temperature under transient summer conditions.

The purpose of this first field survey, which was limited to only one building was therefore:

- To compare measurements and votes of thermal sensation and thermal comfort in a naturally ventilated office and laboratory building under German summer climate conditions.
- To compare these results with different international approaches—particularly 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.

The second study focused on the overall occupant satisfaction with the workplace as well as the occupants' rating of individual satisfaction parameters in different buildings in order to develop a ''satisfaction-index''. Occupant satisfaction, and not just acceptance, in the context of this study is defined as the individual perception of the thermal, visual and audible environment, the air quality at the workplace and the office layout. These are referred to as ''individual satisfaction parameters''. The dependencies between these parameters were evaluated, both in their entirety and in connection with the buildings' design strategy and energy concept.

Another objective of this second study was to find out, whether there are significant differences in the individual satisfaction parameters between the buildings chosen and also between votes in summer and winter. These would allow for general conclusions with respect to energy efficient design features. In this context, the question arose, whether it is possible to ''group'' buildings by the occupants' ratings and if there is an interrelationship between the building's energy and the architectural concept. It was also interesting to determine the importance of the individual satisfaction parameters to occupants and with which sensitivity they affect the well-being and the general acceptance of the workplace.

2. Field study on thermal comfort under summer climate conditions

2.1. 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. As shown in Fig. 1, the building has a net area of approximately 5300 m^2 and includes an older existing part and a new extension built in 2004, both accommodating (mostly smaller) offices as well as laboratories for chemical

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

experiments. Fourteen of the examined 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 year whereas the laboratories are ventilated mechanically due to the special requirements for these workspaces.

The new extension building was conceived 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. Passive cooling is accomplished by glazing with a high selectivity, an external shading system to reduce solar loads during summer and exposed concrete ceilings to 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 skylight windows in the offices.

Compared to an air-conditioned building, no (electrical) energy is needed for cooling the offices in the new extension, which results in a low primary energy consumption. The indoor climate is influenced by the outdoor climate, the user behaviour and the settings of the controls for night ventilation. 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

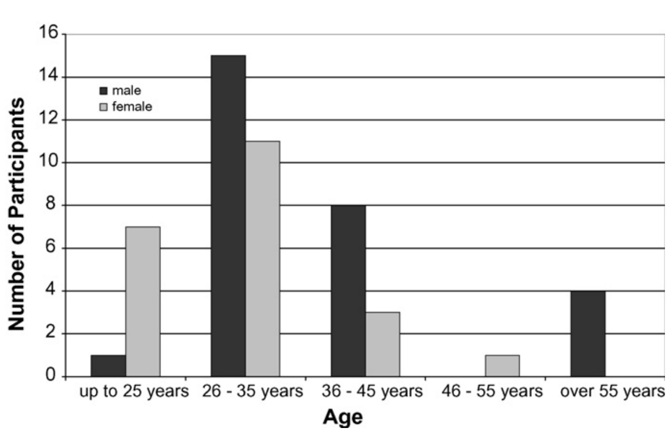

Fig. 2. Distribution of age and sex of the participants.

mean participation rate was 8.5 for all subjects, 427 questionnaires in total were available for the statistical evaluation. Fig. 2 shows the distribution of the participants' 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 min before the surveys. 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 from the questionnaire ranged from 0.33 to 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 surveys 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 Chi^2-test was used and for metric data the analysis of variance was applied with a level of significance of 0.05.

2.2. Results of questionnaires and measurements

Fig. 3 shows the outdoor climate conditions during the whole study. They represent a typical but not very hot summer month for Karlsruhe with temperature maxima above 30 °C on 5 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.

The resulting indoor temperatures for this period are given in Fig. 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 K higher on average and the temperatures on the top floor are 2.8 K higher than on ground floor on 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 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 (far) below 20 °C at the same time. The second floor of the old building part without night ventilation hardly showed any

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

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

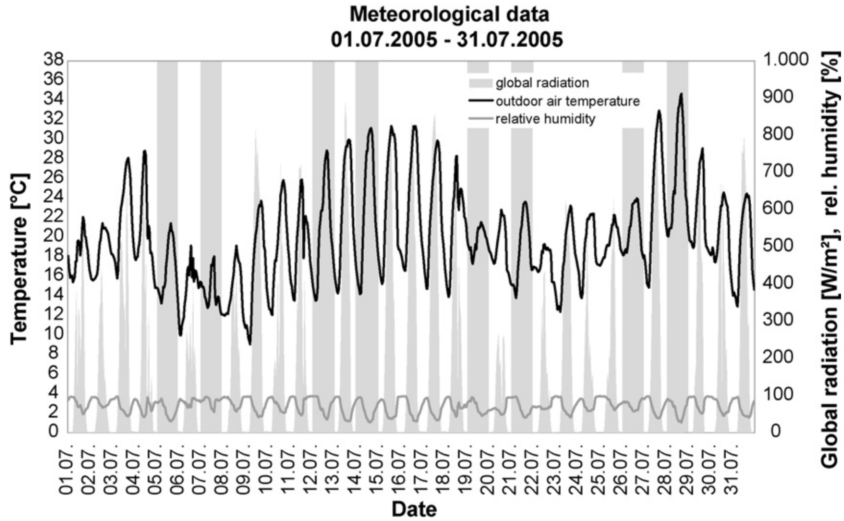

Fig. 3. Outdoor climate data during the period of the study. The light grey bars indicate the days on which surveys and measurements have been carried out.

cooling effect during the nights whereas the ground floor had the same characteristic as the new extension.

In Fig. 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 in operative temperatures of more than 5 K and also include temperatures above 27 °C. The votes for ‘‘very warm’’ (7% of all votes) cover a range from 25 to 30 °C. 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. Fig. 6 shows that temperature ranges for thermal sensation votes are different in the mornings (8 a.m. to 10 p.m.) than in the afternoons (2–4 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. 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 15–30 min before the afternoon survey.

On all 8 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 also give a diffuse picture. 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

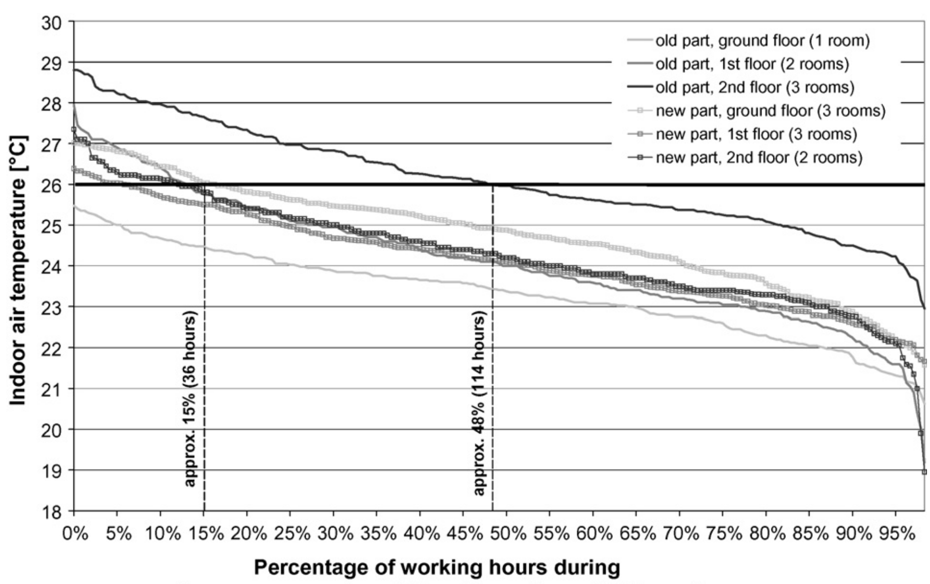

Fig. 4. Indoor air temperatures in the rooms where the surveys were carried out. The bold black line at 26 °C corresponds to the temperature limit of the German workplace regulations.

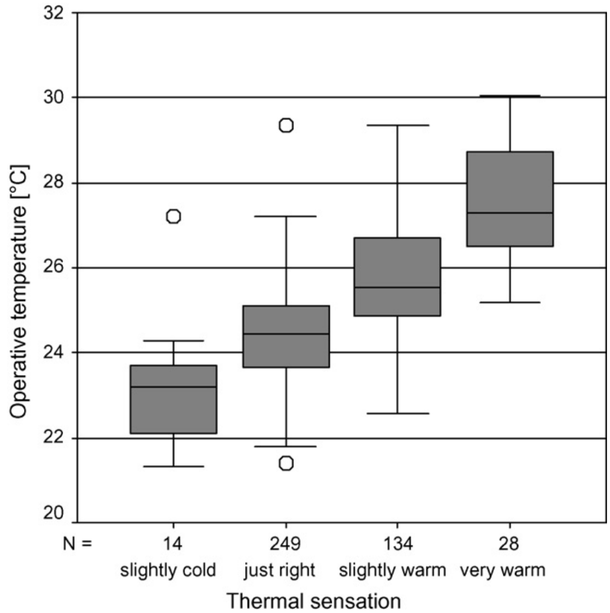

Fig. 5. Box plot of votes of thermal sensation against operative temperature in the rooms. The lines in the boxes represent the median values, the grey boxes cover the mean 50% of the values and the thin lines show the whole range of all values. The small circles indicate outlines. The analysis of variance shows a significant correlation between operative temperature and votes of thermal sensation ($\alpha = 0.05$, $p < 0.001$, $N = 425$).

unexpected changes in temperature. However, the number of votes/subjects is too small to obtain statistically significant correlations.

Though a broad range of air velocities was measured within the rooms, the perception of air movement showed only small differences in the occupants' ratings. This can probably be explained by the measurements themselves. They could only be carried out 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: $\alpha = 0.05$, $p < 0.001$, $N = 211$). Particularly, when the sensations ''slightly warm'' or ''warm'' were chosen, occupants wished to have stronger air movement. The air quality was generally evaluated to be 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 with operative temperatures, analysis of variance: $\alpha = 0.05$, $p < 0.001$, $N = 424$).

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). Fig. 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.

The votes on thermal sensation do not correspond significantly to predicted mean votes, which were calculated with the data measured during the surveys (see Fig. 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 include negative values indicating a cool or even cold indoor environment.

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

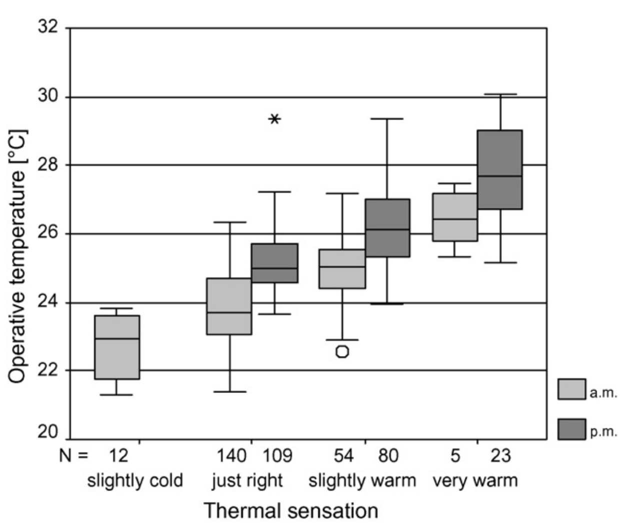

Fig. 6. Box plot of votes of thermal sensation against to the operative temperature in the rooms. The light grey boxes cover the mean 50% of the values in the mornings, and the dark grey boxes show the votes in the afternoons. The group ''slightly cold'' in the afternoon ($n = 2$) has been excluded in the box plot. The analysis of variance shows a significant difference between votes in the mornings and in the afternoons ($\alpha = 0.05$, $p < 0.001$, $N = 425$).

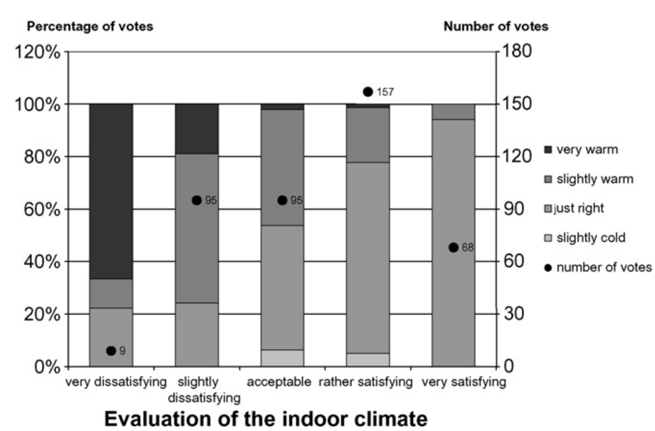

Fig. 7. Relationship between votes of thermal sensation and overall satisfaction with the indoor climate.

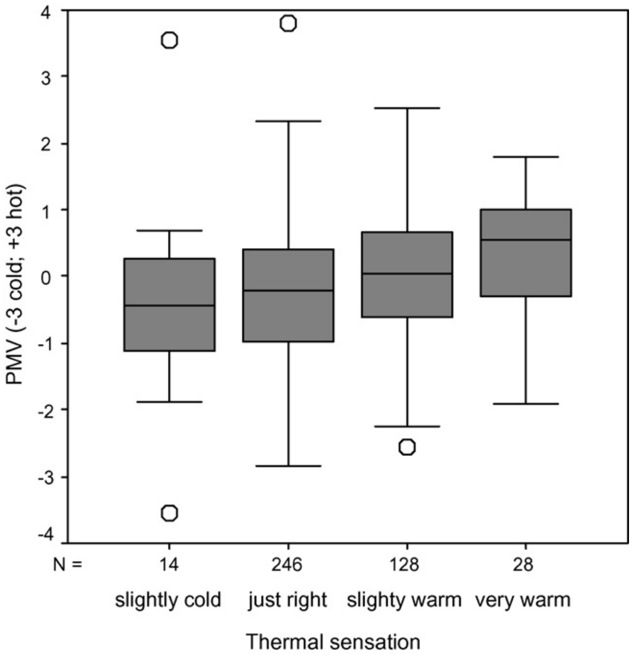

Fig. 8. Comparison of votes on thermal sensation and predicted mean votes according to ISO 7730. The lines in the boxes represent the median values, the grey boxes cover the mean 50% of the values and the thin lines show the whole range of all values. The small circles indicate outlines.

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.

2.3. Discussion of the results

The methodology of the survey proofed to be practicable. All surveys and measurements in the 18 rooms could be carried out within approximately 2 h (15 min per room). Therefore, two sets of surveys 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.

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).

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 results of the study 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 study).

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 h) 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%).

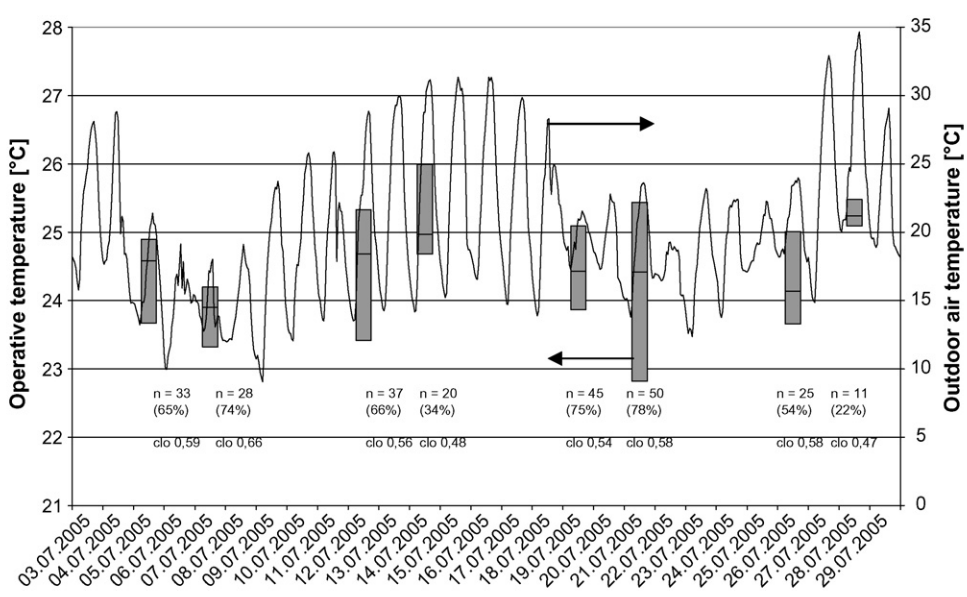

Fig. 9. Outdoor air temperature during the whole study and operative indoor temperatures which were judged ‘‘just right’’; the lines in the boxes represent the median values and the grey boxes cover the mean 50% of the values.

Differences in the occupants' comfort perception between the two parts of the building were not statistically significant.

The deviation of the actual votes of thermal sensation from the 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 be caused by the experimental set-up. The air velocity was measured only at one point in a room and in larger offices this measurement might not represent the actual velocities and the resulting perception of the air movement in the vicinity of the subjects.

It was 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. The latter is in agreement with other research results, e.g. refs. [5,7,9]. The extend to which the results of this survey fit into different comfort models was therefore examined. The fit with the German standard DIN 1946 is unsatisfactory with only 40% of the votes not meeting the boundaries for the indoor temperature. This is due to the fact that in this standard the upper temperature limit is a function of the current outdoor temperature and therefore does not take into account any memory effects. A highly significant correspondence of the comfort votes could be shown with the Dutch model [9] and above all with the ASHRAE model [5]. This suggests that models, which relate thermal comfort to outdoor temperatures in a period prior to the voting better represent the thermal comfort in naturally ventilated buildings.

3. Field study on workplace occupant satisfaction

3.1. Methodology of the study

The surveys for this study were carried out in 16 different German office buildings comprising a variety of sizes and energy concepts. Some of the buildings participated in the research and demonstration programme mentioned above and so featured very low total energy consumptions as well as passive cooling strategies [10,11].

For the study, a questionnaire, which originated at the University of California's Centre of Environmental Design Research, Berkeley, was modified and pre-tested with about 100 persons in three different buildings. The questionnaire had been previously adapted by the authors of this paper for a field study in nine office buildings of the Track Infrastructure Stock Corporation of the German Railway Company (DB Netz AG) [12]. In the questionnaire, all relevant aspects of occupant satisfaction with indoor environments are addressed. The questions address properties directly related to the workplace such as air quality, temperature, air velocity, humidity, acoustics and lighting. In addition, more general questions including office layout, well-being at work, general health, as well as work related factors such as the amount of work, communication between building occupants and the general acceptance of the workplace, are assessed as well. Questions are answered within a 5-point Likert-scale by the participants, but space for comments is provided as well. A copy of the questionnaire used can be found in ref. [10].

Since January 2004, approximately 1300 questionnaires from 16 office buildings across Germany have been evaluated. In each building, surveys were carried out in winter and in summer in order to take into account the influence of diverse climate conditions on the occupants' judgement, particularly the temperature and the lighting levels. The surveys have been carried out anonymously with a random sample size of 30–100 persons per building (depending on the size of the building). A return rate of more than 80% was achieved on average by handing out paper questionnaires personally to the participants. Additionally, room temperatures and humidity values were measured with portable data loggers on the day of each survey. In some of the buildings, more data (e.g. continuously logged room temperatures, opening times of windows, indoor air quality, etc.) were available from monitoring campaigns.

The analysis of the occupants' responses was conducted with the statistical software program SPSS (Statistical Packages for the Social Sciences, versions 11.5 and 13.0). It includes the calculation of mean values, frequency distributions and correlation values as well as a regression analysis for dependent factors. Furthermore, the correlations between independent factors were considered, for example, between the general satisfaction and the individual satisfaction parameters. To identify significant differences in the ratings between summer and winter, an analysis of variance was carried out [13,14]. The hypotheses were statistically tested with a two-tailed alpha level of 0.05; the different sample sizes and the occasional differences in variance have been considered as well [15]. A cluster-analysis was used to identify possible groupings of building characteristics [16].

For evaluating the extent to which the individual satisfaction parameters influence the general judgement of the workplace, the parameters can be correlated with the general satisfaction of the workplace. This leads to weighted values of the importance of each parameter in relation to the general satisfaction. This weighting procedure proved to be more reliable compared to the occupants' judgement, because occupants mostly tend to choose the categories ''important'' or ''very important'' if asked directly.

3.2. Results of the surveys and discussion

In Fig. 10, the mean values of the satisfaction with the room temperature in summer and winter are shown for each surveyed building. The results were calculated with data from the surveys that took place in winter 2004 and 2005 and summer 2004 and 2005.

In summer, the mean satisfaction with the room temperature is about 0.6 scale points below the mean satisfaction in winter. The mean ratings range from ''moderately satisfied'' to ''dissatisfied'' with respect to the perceived room temperature. In winter, the ratings range from ''satisfied'' to ''moderately satisfied''. In four buildings, no significant difference occurs between the seasonal ratings. Considering differences between the buildings themselves the mean rating of the perceived room temperature varies significantly ($p \leq 0.001$).

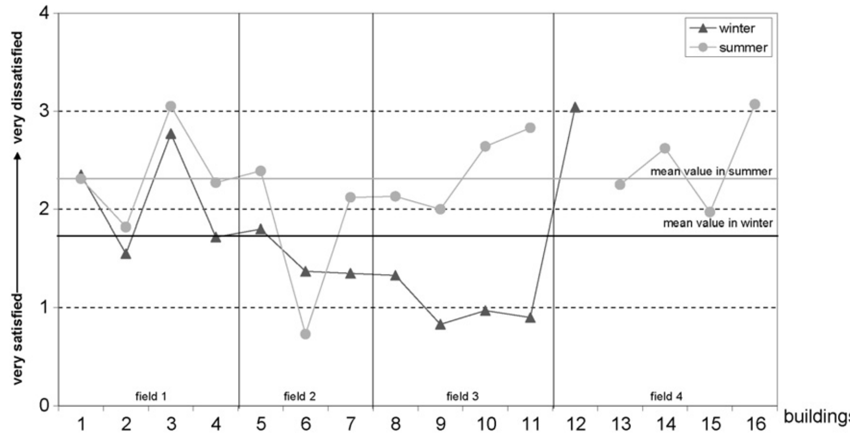

Fig. 10. Mean values of the satisfaction vote with the room temperature during four survey periods (two in winter and two in summer). Where available, the summer and winter ratings are combined. In field 1, there is no significant difference in the satisfaction with temperature between summer and winter ($p > 0.05$). In fields 2 and 3, there is a significant difference between summer and winter ratings (field 2: $p = 0.02$–0.04; field 3: $p \leq 0.001$). In field 4, possible differences still have to be confirmed by the results of the winter survey in 2006.

The differences between summer and winter were calculated with a *t*-test for independent samples for each building using a two-tailed alpha-level of 0.05. This included the Levene-Test for parity of variance. Building no. 6 is the only one in which the mean rating of the summer temperatures was better than the winter rating. It is considered an outlier, which is further examined in the context of the cluster analysis.

A comparison of the perceived room temperatures (too cold, cold, neutral, warm, too warm) with the daily measured room temperatures gives a neutral temperature of almost 23 °C in winter, which is almost 1 K above the mean recommendation of ISO 7730 for this season. In summer, a neutral temperature of 23.5 °C was found which is one degree below the mean recommendation of ISO 7730.

Figs. 11 and 12 show the satisfaction with the room temperature in relation to the measured room temperatures in summer and winter. It seems surprising that the general satisfaction of the perceived room temperature in winter is higher than in summer with similar room temperatures (between 23 and 24 °C). In winter 54% of the occupants in all surveyed buildings are ‘‘very satisfied’’ or ‘‘satisfied’’ with the room temperature whereas in summer the value was only 30%. In the winter surveys the dissatisfaction with temperature often corresponds with the sensation of being ‘‘too cold’’ and the feeling of draft. In summer, the dissatisfaction with the room temperature is mostly associated with the sensation of being ‘‘too warm’’ as well as with dissatisfaction of the indoor air quality. Furthermore, the ratings for fatigue correlate with the perception of room temperatures that are ‘‘too warm’’ and a negative self-assessed job performance.

A stepwise regression analysis that took into account all temperature related variables showed that in winter the satisfaction with the effectiveness of attempted temperature changes, and the perceived dryness of indoor air influence the general satisfaction with the room temperature. In summer, the most important factor was the satisfaction with the effectiveness of attempted temperature changes followed by the perceived indoor air quality having the greatest effect on the satisfaction with the room temperature. This means, that even more than the perceived temperature (too cold, too warm) itself, the number of attempts to change the room temperature and the success of these changes, or in a broader sense, the ability to

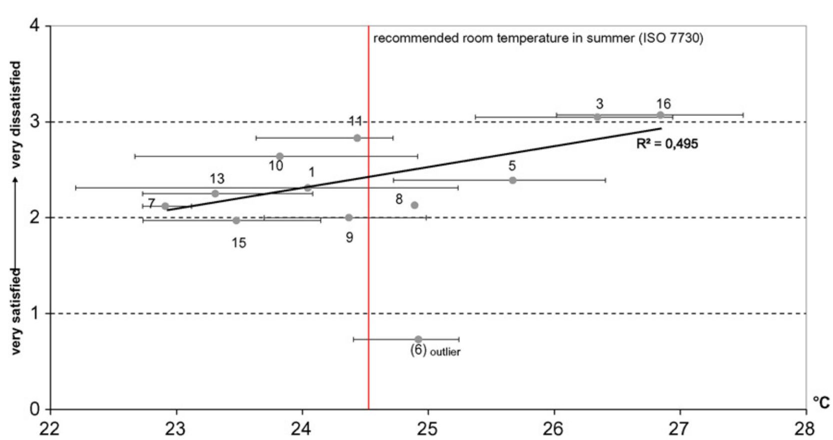

Fig. 11. Mean satisfaction vote with respect to room temperature in summer vs. the measured room temperature (mean value of six rooms measured between 10 a.m. and 3 p.m. on the day of the survey).

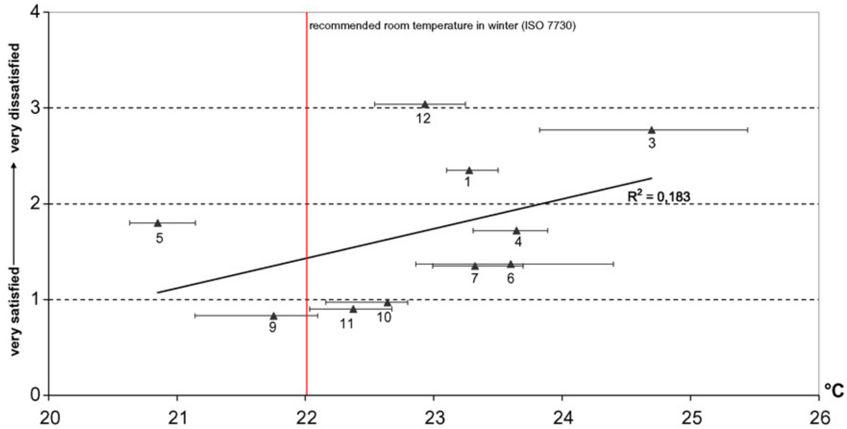

Fig. 12. Satisfaction vote with respect to room temperature in winter vs. the measured room temperature (mean value of six rooms measured between 10 a.m. and 3 p.m. on the day of the survey).

influence the room temperature has a strong influence on the occupant satisfaction. There is some evidence that the stronger dissatisfaction in summer can be explained to a certain extend by the reduced ability to influence the room temperatures. This still needs to be confirmed by analyzing the differences between the buildings with high and low controllability of the indoor climate.

The perception of humidity, especially in winter has a high and significant effect on the ratings of satisfaction with room temperature and perceived indoor air quality, but a very low effect in summer. By correlating the measured mean values of relative humidity (as well as absolute humidity) and the occupant's ratings of perceived humidity, no relationship is evident. The perception of the indoor air quality does not depend significantly on the seasons in most of the buildings. Moreover, only a weak correlation with perceived odours could be observed. In winter, the indoor air quality is mostly related to the perception of dry air. In contrast, in summer the indoor air quality is mostly related to the satisfaction with the room temperature and therefore perceived high temperatures.

To see whether it is possible to group the buildings according to the occupants' satisfaction, a hierarchical cluster analysis was chosen. This analysis was carried out for each subject since a building that performs well concerning noises and office layout, may not necessarily be satisfactory with respect to temperature and indoor air quality. The cluster-analysis that was calculated for the summer surveys, included the following variables:

- current perception of room temperature;
- perception of room temperature in the mornings;
- perception of room temperature in the afternoons;
- perception of temperature changes during the day;
- frequency of attempted active temperature changes;
- satisfaction with effectiveness of attempted temperature changes;
- general satisfaction with room temperature;
- satisfaction with indoor air quality;
- fatigue and lack of concentration;
- dry nose, dry eyes.

The results of this analysis are given in Table 1. Linkages between the first seven buildings listed were found as well as linkages between the next six buildings. Building nos. 3 and 6 cannot be linked with the other buildings. This confirms that before any other conclusions can be drawn, especially building no. 6 must be considered unique at least concerning the questions regarding thermal comfort.

It is evident that the clustering of the buildings according to the mean values of the surveyed parameters (temperature, indoor air quality, self-assessed fatigue and lack of concentration) is reflected in the different energy concepts of the buildings. The first group in Table 1 (light grey) represents those buildings with a medium to high glazing fraction. In four of them, slab cooling systems are installed. Five of the buildings of this group have a large number of offices that are adjacent to an atrium. The way in which this feature can be used qualitatively for the evaluation has still to be investigated.

The buildings in the second group (dark grey) partly share the feature of night-time-ventilation and intermediate glazing fractions. The last two buildings have a completely different architectural concept. No. 3 has a double façade and a very high glazing fraction. The satisfaction with the indoor climate is very poor due to difficulties in operating the HVAC systems and very warm temperatures in the offices especially on sunny winter days. Building no. 6 satisfies the passive house standard and features a low glazing fraction for an office building. The satisfaction in this building is very high due to very effective operation of the building systems. Temperatures are moderate even on bright summer days.

An explorative approach by means of a discriminant analysis revealed that the largest difference between the clustered buildings can be found within the mean votes of the perceived temperature in the mornings. The room temperature in buildings of the first group is perceived as more or less neutral. In the buildings of the second group, it is considered to be "too warm". There is almost no variance between the mean votes of the buildings within both clusters. The general satisfaction with the room temperature is higher in the buildings of the first cluster. Regarding the variables of the cluster analysis which are related to the perceived temperature, building no. 6 can be

Table 1
Specifications of the energy concepts of the clustered buildings and assumed linkages between them

energy concept	07	13	02	04	01	09	15	05	08	10	14	11	16	03	06
natural ventilation	(x)	x	x	x	(x)	x	x	x	x	x	x	x	x	(x)	x
night ventilation		x					x	x	x	x	x			x x	
supply air	x	x		(x)	(x)				x		(x)		(x)	x	
exhaust air	x	x		(x)	(x)			x	x	x	(x)		(x)	x x	
humidifica-tion	x				(x)										
radiator	x	x	x		(x)	x	(x)	x	x	x	x	x	x	(x)	
slab cooling	x	x	x		x									x x	
atrium	x	x	x		x		x								
double facade			(x)		x									x	
suspended ceiling				(x)		(x)					(x)				
glazing proportion	55 %	35 - 65 %	60 %		90 %		26 %	35 %	40 %	30 %		40 %		90 %	23 %
shading/glare protection	i	i	e	e	s	e	e	e	e	e	e	e	e	s i	
free-running		x	x	x		x	x	x	x	x	x	x	x		
partly air-conditioned					x							(x)		x x	
fully air-conditioned	x														

For the shading: i = internal, e = external, s = between the panes.

assigned to the first cluster and building no. 3 to the second cluster. But buildings 3 and 6 are not part of the two clusters because there are differences, e.g. within the variables ‘‘perceived temperature changes’’ and ‘‘satisfaction with effectiveness of attempted temperature changes’’.

Looking at the impact of the satisfaction with the room temperature on the general satisfaction with the building, there appears to be inconsistency among the buildings as well as between summer and winter surveys. Because the correlation between the satisfaction-parameters and the general satisfaction with the workplace often varied remarkably from building to building, a scale is introduced, which includes the following parameters:

- satisfaction with daylight;
- satisfaction with artificial light;
- satisfaction with room temperature;
- satisfaction with indoor air quality;
- satisfaction with noises;
- satisfaction with office layout;
- satisfaction with cleanliness of the office.

The reliability of the scale was tested with Cronbach’s alpha coefficient and showed, that the single parameters can be combined completely. The scale also reflects the general satisfaction with the workplace very well. The correlation coefficient (Spearman) between the scale value and the general satisfaction with the workplace is 0.685 ($p \leq 0.001$).

Fig. 13 gives an example of using surveys for the assessment of building operation. It shows the satisfaction with the temperature together with its weighted importance for the general satisfaction with the workplace. In particular, the buildings that are situated in field D call for action concerning the thermal comfort at the workplaces, because the occupants are dissatisfied with the prevalent temperatures and the temperature is weighted as rather important for the general satisfaction with their workplace. This also might affect their productivity. The diagram shows that in summer (grey spots) the importance of an adequate room temperature and the ability of (successful) intervention are more important for the general satisfaction than in winter. In the buildings in field C, a great dissatisfaction with the room temperature can be found in winter and summer. While the dissatisfaction in these buildings also implicates a great potential for improvements of the HVAC equipment, other parameters seem to be more important for the general satisfaction with the workplace, for example, the office layout and interferences because of noises.

Buildings in fields A and B are not critical with regard to the parameter ‘‘satisfaction with room temperature’’, because the occupants are rather satisfied on average. In some buildings, the parameter influences the judgement of the general satisfaction positively. The positive judgements come almost exclusively from the winter ratings—except no. 6, which was discussed before.

4. Summary and general conclusions

The first study showed that naturally ventilated and passively cooled buildings can be highly appreciated by

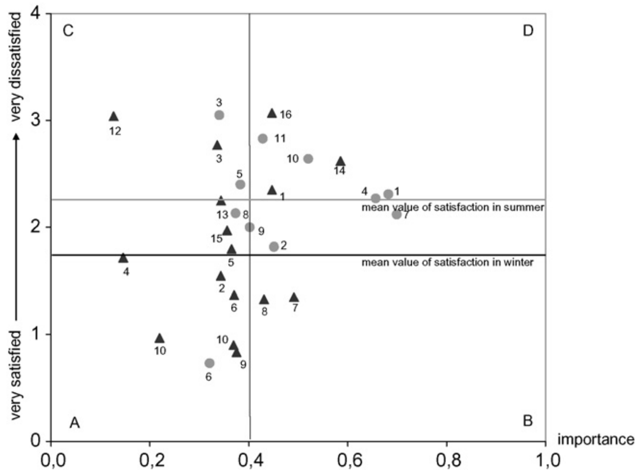

Fig. 13. Correlation between mean satisfaction with the temperature and weighted importance of the temperature for the general satisfaction with the workplace (Spearman correlation). Region A (lower left): Occupants are satisfied with the parameter but the weighting calculation shows that it is less important for the general satisfaction with the workplace. Region B (lower right): Occupants are satisfied with the parameter and it is important for the general satisfaction with the workplace. Region C (upper left): Occupants are dissatisfied with the parameter but it is of less importance for the general satisfaction with the workplace. Region D (upper right): Occupants are dissatisfied with the parameter and it is very important for the general satisfaction with the workplace.

occupants during summer if they are designed properly in terms of the indoor climate. Positive perceptions of thermal comfort can occur outside the temperature limits set in standards for air-conditioned buildings. The study therefore confirms that adaptive comfort models predict the thermal sensation and thermal comfort of occupants better than models with a fixed limit to the indoor temperature, 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.

The second study which covered surveys in summer and winter revealed that the occupants' control of the indoor climate and moreover the perceived effect of their possible different interventions strongly influence the satisfaction with thermal indoor conditions both in winter and in summer. Since the potential for a successful intervention is higher in winter due to a larger temperature difference between indoors and outdoors, the satisfaction with the room temperature was lower in the summer surveys. It was further investigated whether the evaluation of a building's energy concept, with regard to thermal comfort, can be supported by a cluster analysis. The method showed some promising results with finding groups of buildings with the same technology features but further research has to be done to gain reliable results for comfort relevant building features.

By correlating individual satisfaction parameters with the general satisfaction with the workplace, a weighted importance for each parameter can be gained. This method of ranking the individual satisfaction parameters provides a more straight-forward assessment of building operation by showing the optimisation potential for each comfort parameter. In combination with the mean values of the satisfaction parameters, the need for changes in the building and the possibility to raise the occupants' productivity becomes transparent to the building manager. This includes not only the operation of technical systems but also the appropriate behaviour of the occupants according to the specific building concept. By comparing the mean values and variances of the satisfaction parameters of buildings, it still has to be ascertained, where the borders of the satisfaction fields will finally be situated.

The large variety of architectural and technical concepts for buildings only allows a qualitative evaluation of their effect on the occupant satisfaction at the moment. Further evaluations of the data gained in the surveys will concentrate on proving whether certain energy-conscious design features show the intended positive effect on the occupants. This will include investigations of the degree to which occupants are normally dissatisfied with certain features and to what extend factors like gender, job structures and others are more important than architectural influences.

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