Proceedings of 8th Windsor Conference: ***Counting the Cost of Comfort in a changing world*** Cumberland Lodge, Windsor, UK, 10-13 April 2014. London: Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Presenting LOBSTER, an innovative climate chamber, and the analysis of the effect of a ceiling fan on the thermal sensation and performance under summer conditions in an office-like setting

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Abstract

Thermal comfort studies have been performed so far either in closed climate chambers with controlled conditions or non-controlled conditions during field studies. Detailed analyses of mechanisms behind the adaptive comfort models are therefore hardly possible. This paper presents a newly constructed climate chamber in Karlsruhe (Germany) along with the complete chain from subjective experiments, via data analyses, model development and implementation into dynamic building energy simulation until the formation of a decision base for or against a renovation measure for a confined case. The objective of this experimental series conducted in summer 2013 was the analysis of the effect of a ceiling fan on the perceived thermal comfort and performance. The results suggest that it is not the control itself, which leads to a higher acceptance of increased indoor temperatures in summer, but the effectiveness of the control. For the analysis of the performance tests, only minor differences in the performance under the distinctive conditions were observed.

Keywords: Adaptive comfort, fan usage, occupant behaviour, neutral temperature, simulation

1 Introduction

The foundations of thermal comfort studies have been laid in closed climate chambers (Fanger, 1972). Today these studies are criticised for the lack of adaptive opportunities subjects had during the experiments. At the same time, the studies conducted within the development of the adaptive comfort model are field studies missing controlled conditions (deDear et al., 1997, Humphreys and Nicol, 1998). Detailed analyses of individual portions of the adaptive mechanisms are therefore hardly possible on the existing dataset.

This paper presents a newly constructed climate chamber in Karlsruhe (Germany) along with the results of a first experimental series conducted during the summer 2013. These results are implemented into a dynamic building simulation in order to form a decision base for renovation measures.

The objective of the first experimental series was the analysis of the effect of a ceiling fan on the perceived thermal comfort and mental performance. The ceiling fan was chosen because it is - compared to others - a rather cheap investment which could be applied easily during remodelling projects.

The hypotheses tested were related to differences in the thermal sensation, acceptance and preference votes as well as the results of the performance tests between three conditions. Their distinction was based on the degree of permitted ceiling fan usage.

2 LOBSTER – an adaptive test facility

The Laboratory for Occupant Behaviour, Satisfaction, Thermal comfort and Environmental Research (LOBSTER) was designed for studies on adaptive comfort and occupant behaviour.

In order to facilitate studies on adaptive comfort, the two identical fully equipped office rooms have one façade to the outdoor environment (see Fig. 1). Each office room has integrated in the post and beam structure made of insulated aluminium profiles two windows and two top light windows. The windows can be opened and tilted; the top light windows can only be tilted (see Fig. 2). The glazing is a triple glazing; the opaque balustrade is equipped with vacuum insulation panels. The windows are tilted mechanically either by pressing a button on the window catch or through the building control system. Opening the windows has to be done by hand.

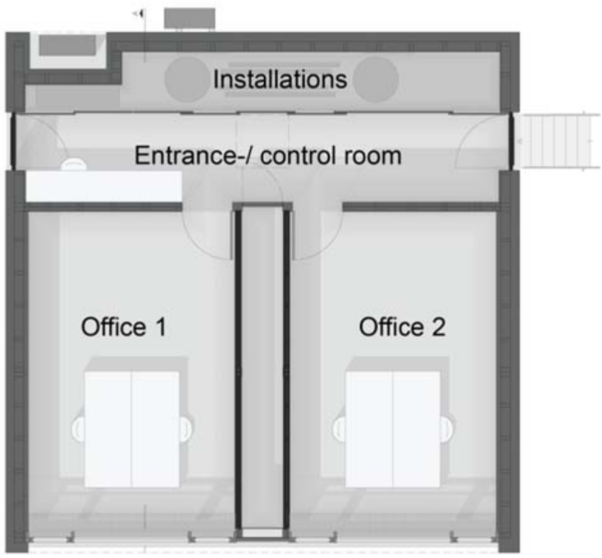

Figure 1. Floor plan

Figure 2. One of the office rooms

In addition to the possibility to open one or both of the windows, the ventilation concept involves two decentralized floor convectors able to heat or cool the inlet air before entering the office space and a fan driven exhaust system in the back of the room.

The whole of the glass surface can be shaded by electrically driven Venetian blinds with daylight guidance from ROMA (see Fig. 3). The daylight guidance provides daylight through the upper part even when the lower part of the blinds is completely closed.

With respect to studies on occupant behaviour, subjects can be granted – depending on the experimental setup - multiple adaptive opportunities such as controlling the window opening, the Venetian blinds or a ceiling fan (see Figs. 2 and 3). On the other hand, all those interactions – except a full opening of the windows – can be done by the researcher or an algorithm through the building control system accessible for the researcher through LabView.

Five of six surfaces (all except the post and beam façade) are activated with a capillary tube system, which allows changing the set point temperature of each wall surface individually. In the framework of these experiments the control of the surface temperatures was not in the hands of the subjects – in fact, they were not told that such panel exists.

Figure 3. Venetian blinds with daylight guidance

3 Experimental design

The experimental design presented by Schweiker et al. (2012) was adapted to suit the current objectives. With the focus on the effect of a ceiling fan, only three conditions were chosen: i-, i+, and iP.

During the i- conditions, the subjects were allowed to control the window opening, sun protection state and lighting level. During the i+ settings, they were able to control the ceiling fan state in addition to the controls of the i- setting. The usage of the ceiling fan was also allowed during the iP conditions. Thus, the ceiling fan was set on reverse mode, so that its effect on changing the air velocity at the work space was reduced to a minimum.

In addition, the set point temperatures of the wall surfaces and the air supply were controlled non-steady-state. They stayed at 1K below the adaptive comfort temperature calculated according to DIN EN 15251 between 9am and 9:30am. From 9:30am until 4:30pm their set point temperature was increased linearly from 1K below the adaptive comfort temperature until 3K above it, i.e. at the end of the day, they were 1K above the comfort band according to category I (see Fig. 4). Under the postulate of the adaptive comfort model, one can expect that the thermal strain is comparable from day to day despite changes in the outdoor weather conditions.

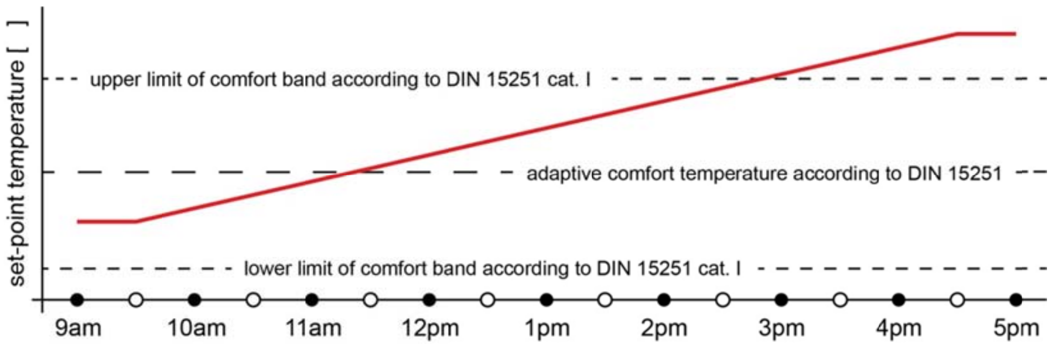

Figure 4. Temperature profile of wall surfaces and the air supply system

Table 1. Average and standard deviation of subjects' gender, age, height and weight

	N	Age [a]	Height [cm]	Weight [kg]
Female	10	25 (sd=4.6)	170 (sd=6.0)	63 (sd=7.0)
Male	11	25 (sd=4.0)	187 (sd=5.8)	83 (sd=10.8)
All	21	25 (sd=4.2)	179 (sd=10.6)	73 (sd=13.7)

In total 21 subjects (11 male, 10 female) were chosen as subjects based on their health conditions. Table 1 summarizes their basic characteristics.

The subjects were asked to work on their own during 3 consecutive days for 8 hrs (from 9 am till around 5 pm with 30 min lunch break) in the test facility. Each of the three distinctive sessions introduced above had to be conducted once. The order of conditions was randomized, i.e. around one third of the subjects started with i-sessions, the next third with i+ sessions and the last group with iP sessions.

Every morning, the subjects were told, whether they could use the ceiling fan or not. The mode of the fan (reverse or not) was not communicated. The ceiling fan was controlled by the subjects via a web-based interface, which was unlocked during i+ and iP-sessions.

During the day, subjects had to fill out a computer-based 5-minute comfort questionnaire with 30 items roughly every 90 minutes (see Fig. 5). The questionnaire was used to assess the thermal sensation vote (ASHRAE 7-scale), thermal preference (4-scale), thermal acceptance (4-scale), perceived air movement, preferred air movement as well as three items related to the perceived levels of pleasure, arousal and dominance (Lang et al., 1993).

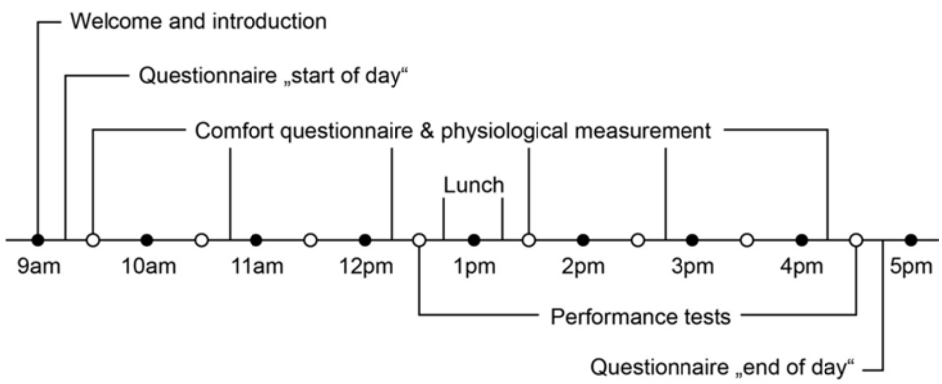

Figure 5. Timeline of surveys and physiological measurements

Twice a day (before lunch and before the end of the experiment), they had to do three performance tests in a row: the Tsai-Partington, addition and the d2 taking in total 15 minutes.

For the Tsai-Partington, subjects were given two sheets of papers with 25 randomly distributed numbers from 1 to 99. They had to link the numbers in ascending order within 40 seconds for each sheet (Ammons, 1955). The addition task took 5 minutes within which the subjects had to solve as many additions of 5 two-digit numbers as possible (Wargocki et al., 1999). The d2 is a test for the assessment of selective attention and concentration (Brickenkamp, 2002).

In addition, physical parameters of the indoor and outdoor environment such as air temperature, surface temperatures, humidity, and air velocity were measured continuously in a one minute interval.

3 Hypotheses

The hypothesis regarding the thermal comfort votes obtained in each session are shown for the thermal sensation vote in Figure 6. Due to the higher degree of control together with an increased air velocity, the thermal comfort votes obtained in condition i+ are suspected to be higher, i.e. closer to neutral, compared to the i- sessions. For those obtained during the iP sessions two outcomes are possible according to the literature. They could be higher due to the higher degree of control or lower due to a non-efficient control and corresponding dissatisfaction.

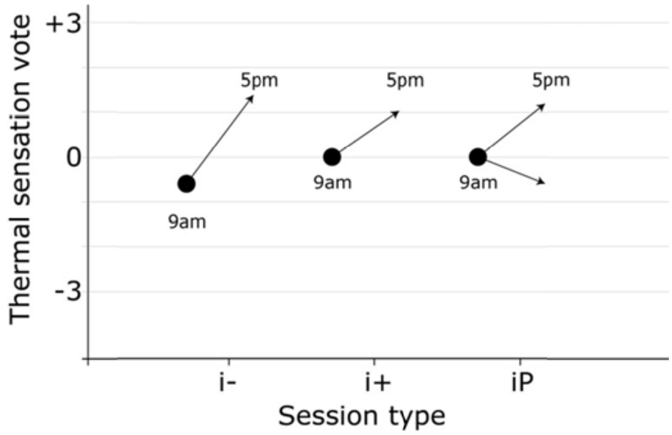

Figure 6. Hypotheses related to session type and thermal comfort votes.

4 Analysis methods

4.1 Data preparation

Besides data maintenance, the following items were derived from one or more directly observed values:

- The operative temperature was derived based on air temperature, globe temperature and air velocity measured adjacent to the workplaces close the middle of the room.
- The neutral temperature by Griffith' method, T_{nG}, was calculated for each vote according to the modifications described by Rijal et al. (2008), which gives the neutral temperature to be

$$T_{nG} = T_g + (0 - TSV) / R, \quad (1)$$

with T_g being the globe temperature and R a factor representing the expected change in TSV for each degree rise in the globe temperature. T_g is used as an approximation to operative temperature in their study, so that T_o could be used for this study without problems. R was set to be 0.33, which is related to the findings of Fanger (1972) that, all else being equal, the comfort vote increases by one unit for each three degree rise in globe temperature.

- For the addition task, the speed was calculated according to the number of correct answers per second.
- For the Tsai-Partington-test, the total number of correct links was calculated for both sheets, representing the total number of correct links within 80 seconds.
- For the d2 test, the concentration performance was calculated according to Brickenkamp (2002).

4.2 Statistical analysis

In order to reveal differences between the sessions in thermal comfort votes and performance the Wilcoxon signed rank test for related samples (Wilcoxon, 1945) was evaluated using the statistical software SPSS. As input to the test, a) the means of all measurements for each session type (experimental day) were calculated for each subject and b) the means of the last two measurements of each session type (day) were taken.

The usage of the ceiling fan was recorded in percentage of the maximum speed. For the model development, these values were recoded to show “0” when the fan was switched of and “1” in the other case. Such dichotomous data can be used to derive a logistic regression model of the form

$$p_{\text{Ceiling fan}} = \frac{1}{1+\alpha\, e^{-(\beta\, \theta_{Op})}} \quad , \tag{2}$$

with $p_{\text{Ceiling fan}}$ being the probability that one can observe the ceiling fan being switched on, α and β the coefficients derived and θ_{Op} the operative temperature.

4.3 Implementation into dynamic building simulation

The logistic regression model of ceiling fan usage for the i+ session was then implemented into a dynamic building simulation. First, an idf (EnergyPlus) model of a simple 4m width and 6m deep office cell with the South facing wall adjacent to the outdoors was created using DesignBuilder. The South façade has a wall-to-window ratio of 50%. The walls have a U-value of 1.5 $W/(m^2\ K)$, the window a U-value of 1.72 $W/(m^2\ K)$ and a g-value of .69 representing an existing not refurbished building standard from before 1978 in Germany. The building was situated in Freiburg/ Germany. There was neither cooling nor a sun shading device implemented. Schedules and activity levels were chosen to be typical for an office.

The idf model was then coupled via MLE+ (Nghiem, 2014) with a MatLab-model containing the code for the probabilistic ceiling fan usage model. Though, EnergyPlus does not offer a ceiling fan, for each timestep, the prevailing operative temperature was passed from EnergyPlus to MatLab. Within MatLab the probability of the ceiling fan was calculated according to the logistic regression model and compared to a random number. In case the random number was higher than the probability, the ceiling fan was considered to be switched on. At the end of each of the 100 simulation runs, the number of timesteps the ceiling fan was switched on was summed up and multiplied by 100W, which was considered to be a medium power.

In addition, the number of hours being outside the comfort range was derived. The comfort range was defined as 2K above the median neutral temperature observed during i- and i+ sessions.

5 Results

Figure 7 presents the mean difference together with the standard deviation between operative temperature and adaptive comfort temperature for each session type at the times of the comfort votes. In addition the set point according to the experimental design is shown. While i- sessions tend to be cooler at the end of the day than scheduled, i+ and iP sessions are in the middle of the day up to 2K higher than set. The latter is due to the simple control algorithm implemented during this first series of measurements. Due to time constraints in the preparation phase the control did not react to increased thermal loads either solar or due to any occupancy.

In Figure 8, set point, measured surface, air and derived operative temperatures are shown alongside with the behavioural variables for the window, ceiling fan and sun protection states. The temperatures show that real conditions were warmer than they were meant to be as explained above.

The total number of votes in total and for each session type is shown in the first column of Table 2. With all 21 subjects giving all votes, a total of 126 votes per session were expected. The missing votes happened due to subjects having been to the restrooms short before a scheduled vote, or having been absent due to important meetings, which could not have been avoided.

The mean values and standard deviations of running mean outdoor temperature, T_{rm}, operative temperature, T_{op}, relative humidity, RH, and air velocity, v, are presented in the following columns of Table 2. The mean T_{rm}'s are very similar, while T_{op} and v differ. The latter was expected due to the difference of ceiling fan usage, while the former was due to different interactions of subjects with their controls.

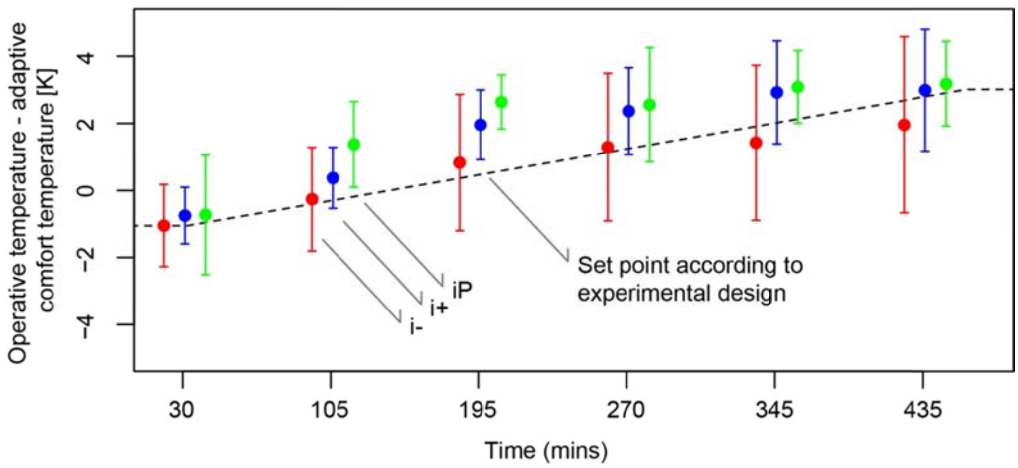

Figure 7. Mean and standard deviation of the difference between operative temperature and the adaptive comfort temperature for each session type and interval of comfort vote. The dashed line shows the set point according to the experimental design.

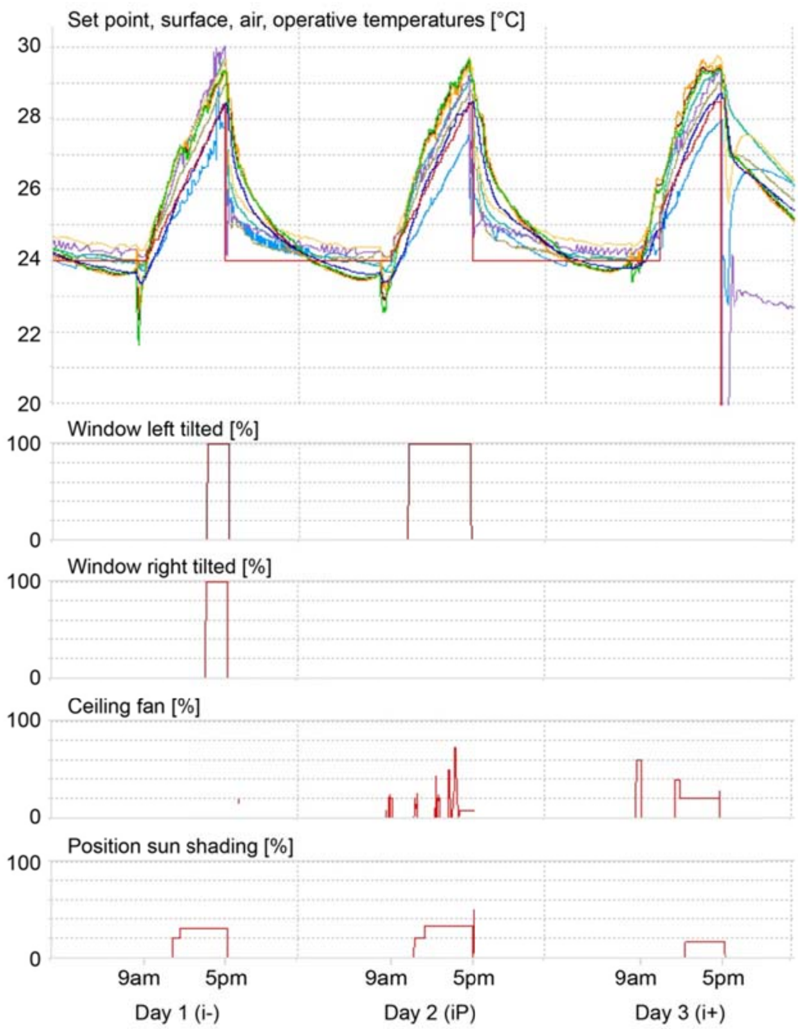

Fig. 8. Example of temperature values and behavioural data for one set of experiments, i.e. three experimental days (in this case the first day was the i- session). The red line in the top element shows the set point temperature for the surfaces; the operative temperature is drawn in purple, the air temperature in green and the other colours represent the five surface temperatures.

Table 2. Number of votes, mean values and standard deviations of thermal sensation vote, TSV, running mean outdoor temperature, T_{rm}, operative temperature, T_{op}, relative humidity, RH, and air velocity, v, for the full data set and each condition

Data (subset)	N	TSV	T_{rm} [°C]	T_{op} [°C]	RH [%]	v [m/s]
all	356	4.4 (0.9)	19.3 (1.5)	26.7 (2.3)	45 (7)	0.17 (0.15)
i-	119	4.4 (1.0)	19.1 (1.5)	25.8 (2.4)	48 (7)	0.11 (0.05)
i+	120	4.2 (0.7)	19.5 (1.4)	26.9 (2.1)	45 (7)	0.27 (0.21)
iP	117	4.6 (1.0)	19.3 (1.5)	27.2 (2.1)	42 (6)	0.14 (0.11)

5.1 Comparison of thermal comfort votes and performance between sessions

Figure 9 shows the mean and standard deviation of thermal sensation votes according to each session type at each survey period. The tendencies vary during the morning (first three votes): the votes obtained during i+ sessions are the lowest, i.e. subjects stating to sense the most comfortable, followed by those from the i- sessions and the iP sessions. The afternoon votes show that the i+ sessions are sensed in average as being most comfortable, followed by the iP and the i- sessions.

The results of the Wilcoxon Signed Rank tests for the daily mean thermal comfort votes and the mean of the calculated PMV for the six measurements are shown in Table 3. For all items except PMV, the Wilcoxon signed-rank test showed a statistically significant change between i- and iP-sessions. In addition, thermal sensation votes differed statistically significant between i+ and iP sessions and neutral temperatures between i- and i+ sessions.

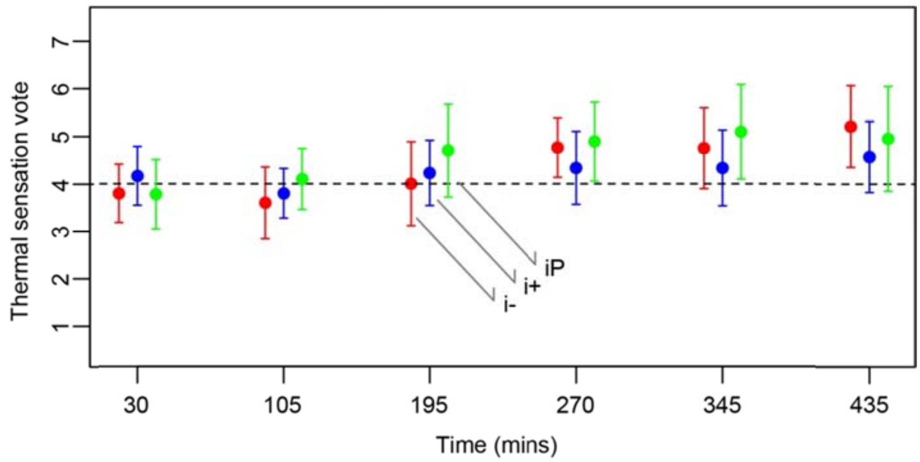

Figure 9. Mean and standard deviation of thermal sensation votes grouped according to session type and binned for each survey period

Table 3. Median, Z- and p-value of Wilcoxon signed rank tests for four items related to thermal comfort. Significant differences ($p<0.05$) are marked with bold characters.

	Median			Result Wilcoxon signed rank test		
	i-	i+	iP	i- to i+	i+ to iP	i- to iP
Thermal sensation vote	4.33	4.17	4.67	-.93 (.353)	**-2.77 (.006)**	**-2.06 (.039)**
Thermal preference	-.33	-.17	-.50	-.992 (.321)	-.766 (.444)	**-2.20 (.028)**
Thermal acceptance	-.50	-.33	-.67	-1.33 (.183)	-.987 (.324)	**-2.74 (.006)**
Neutral temperature	25.1	26.6	25.9	**-2.73 (.006)**	-1.30 (.192)	**-2.42 (.016)**
PMV	.42	.35	.39	-.40 (.689)	-1.65 (.099)	-1.58 (.114)

The results of the Wilcoxon Signed Rank tests for the mean of the last two thermal comfort votes and calculated PMV of each day are shown in Table 4. For all items, the Wilcoxon signed-rank test showed a statistically significant change between i+ and iP-sessions. In addition, neutral temperatures show statistically significant differences between all sessions. There is no statistically significant difference between i- and i+ or i- and iP sessions for the calculated PMV.

The results of the Wilcoxon Signed Rank tests for the performance tests are shown in Table 5. The Wilcoxon signed-rank tests showed that none of the sessions did elicit a statistically significant change ($p<0.05$) in any performance. Indeed, median ratings were close to similar. The analysis of the test batteries performed in the afternoon alone did not show any significant differences either.

Table 4. Median, Z- and p-value of Wilcoxon signed rank tests for four items related to thermal comfort for the last two measurements of the day. Significant differences ($p<0.05$) are marked with bold characters.

	Median			Result Wilcoxon signed rank test		
	i-	i+	iP	i- to i+	i+ to iP	i- to iP
Thermal sensation vote	5.00	4.45	5.05	**-3.07 (.002)**	**-3.00 (.003)**	-.14 (.886)
Thermal preference	-.67	-.36	-.64	-1.91 (.057)	**-2.17 (.030)**	-.073 (.942)
Thermal acceptance	-.76	-.59	-1.0	-1.09 (.276)	**-2.50 (.012)**	-1.14 (.253)
Neutral temperature	23.8	26.9	25.2	**-3.63 (.000)**	**-2.66 (.008)**	**-2.21 (.027)**
PMV	.67	.64	.69	-.295 (.768)	**-1.96 (.050)**	-1.20 (.230)

Table 5. Median, Z- and p-value of Wilcoxon signed rank tests for four items related to performance. “Speed” is the number of correct addition tasks per second, “number of correct links” is the number of correct links drawn on two sheets within 40 seconds each.

	Median			Result Wilcoxon signed rank test		
	i-	i+	iP	i- to i+	i+ to iP	i- to iP
Speed (Addition)	.080	.080	.077	-.469 (.639)	-.035 (.972)	-.785 (.433)
Number correct links (Tsai-Partington)	23.5	23.5	24.0	-.187 (.852)	-.226 (.821)	-.040 (.968)
Concentration performance (d2)	181	187	188	-.261 (.794)	-.052 (.958)	-.052 (.958)

5.2 Logistic model of ceiling fan usage

The logistic regression models for the ceiling fan usage during i+ and iP-sessions are similar (Fig. 10). In both cases, the operative temperature at which 50% of the subjects are using their ceiling fan is around 28°C. Table 6 shows the values for coefficients of the ceiling fan usage model during i+ sessions.

Linear models of the chosen strength (subjects could choose between 0% and 60% of the maximum speed) however show that at the same operative temperature a higher speed was chosen during iP-sessions compared to i+-sessions.

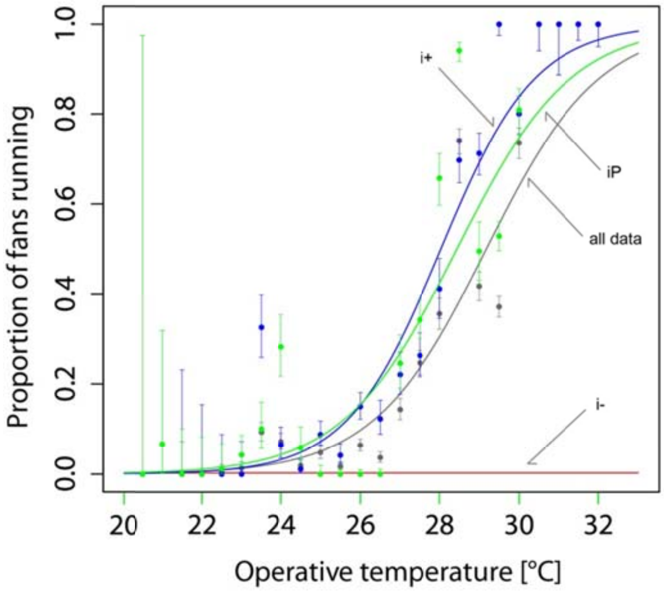

Figure 10. Observed and fitted probabilities to observe the ceiling fan running using the operative temperature as predictor for all data and individual session types

Table 6. Values of coefficients, standard error and probabilities of the ceiling fan usage model during i+ sessions (Nagelkerke's R^2-index for model: .488)

	Value	Standard error	Probability
Intercept	-23.6	±.655	<0.001
Operative temperature	.841	±.0237	<0.001

5.3 Dynamic building simulation

Figure 11 shows the output of 1 of the 100 simulation runs with regard to outdoor air temperature, operative temperature and ceiling fan state. The data of the ceiling fan shows, that the model performs as one would suspect. The usage of the ceiling fan is higher during summer season, than in winter.

Due to the probabilistic character of the model, the usage pattern differs slightly from test run to test run. The minimum total usage time is 756hrs, the maximum 1028hrs with a mean of 893hrs and a standard deviation of 57hrs.

The number of hours outside the comfort range is 1811hrs during i- sessions and 941hrs during the i+ sessions. The comfort range for the i- sessions is 25.1°C ± 2K and for the i+ sessions it is 26.6°C ± 2K. They were obtained using the mean of neutral temperatures stated above.

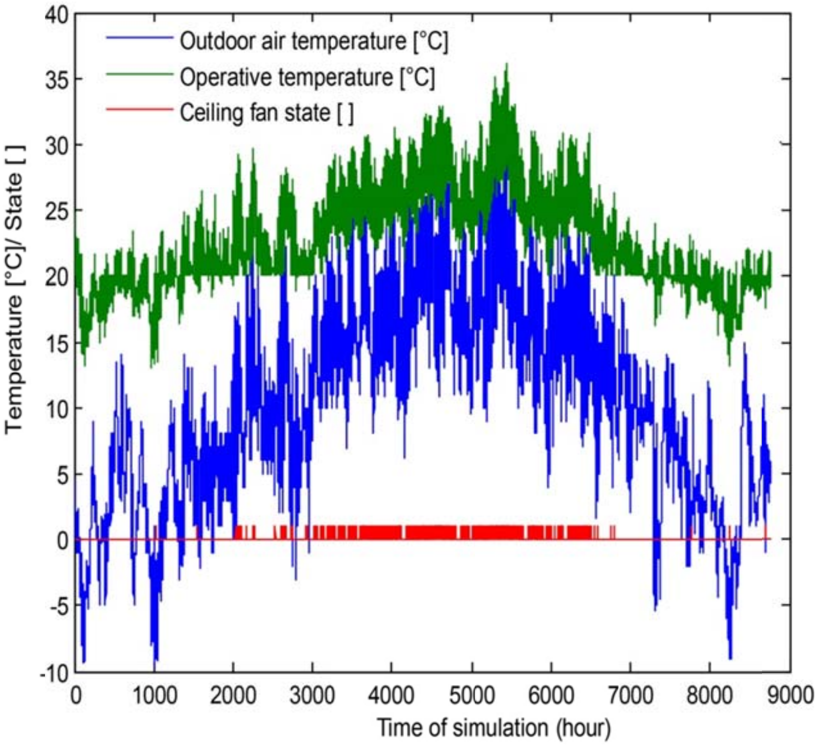

Figure 11. Output of 1 of 100 simulation runs using the probabilistic ceiling fan usage model.

6 Discussion and conclusions

As already shown in Schweiker et al. (2012), careful developed experimental designs implemented in a climate chamber having at least one window facing the exterior are suitable in order to reveal further insights into adaptive processes.

For this project, the effect and usage of a ceiling fan was chosen vicariously for other interactions to be researched. In contrast to the experiments presented in Schweiker et al. (2012), only the interaction opportunities of the ceiling fan differed, while occupants were allowed to open the window and/or use the ceiling fan at all times. Still, a statistically significant difference was found in the mean neutral temperatures for the sessions, when the usage of the ceiling fan was allowed compared to the ones it was not. This complies with findings of previous research (see e.g. Brager et al., 2004), which showed that occupants thermal sensations differs with the degree of control.

The iP sessions were intended to test a so-called placebo-effect of giving subjects control over the ceiling fan, while it does not have any effect. In reality, there was still a not neglectable effect on the air velocity due to the ceiling fan running in reverse mode. With a linear regression analysis, it was further shown that subjects reacted to the difference in the ceiling fan's performance by increasing the speed. In order to level out such effect, allowing the subjects the choice of a single speed could be a solution for further studies.

The analysis of differences in thermal comfort votes between the session types did partly show statistically significant differences, partly not. The analysis of the votes obtained at the last two measurements of each day showed that the neutral temperature, TnG, differs significantly between the three session types. In Figure 9 can be seen, that the thermal sensation vote is higher for i+ sessions compared to i-during the first periods. In the afternoon, the thermal sensation vote is lower, i.e. subjects perceived the conditions as more comfortable. This would support the hypothesis that at the beginning, having control positively influences on the occupants thermal sensation but at the end of the day, such control needs to be effective in order to remain such influence. An analysis compared to the theory of alliesthesia (Parkinson et al., 2012), is difficult to perform based on the existing data due to the number of interaction types and the lack of comfort votes close to the interactions.

The occupant behaviour model for the ceiling fan usage considered in this study – a multivariate logistic regression model – is compared to the models presented in the literature (see e.g. Haldi and Robinson, 2009) one of a simple type. Discrete-time Markov chain models and others would be usefully implemented in order to increase the validity of the results. Such analysis is beyond the scope of this paper and will be presented elsewhere.

The air movement and temperature distribution used for this analysis is based on a one-node-room model. This is valid for the measured data (taken in the middle of the room) as well as the simulated data. Therefore, the validity between statistical model and simulation is given. In order to increase the accuracy, detailed investigations of the air flow profile of the existing ceiling fan as presented in Voss et al. (2013), would be meaningful.

The dynamic building simulation showed, that the elevated comfort range due to the ceiling fan nearly halved the hours with temperatures above the comfort range. In the chosen case study, the resulting hours above the comfort level are with more than 800 hrs still above an acceptable number of around 260 hrs (= 3% of a year as denoted in DIN EN 15251). The reduction of hours outside the comfort range comes through a relatively easy measure.

The installation costs of a ceiling fan could be estimated depending on the situation between 150€ and 500€ per office. The running electricity cost for each ceiling fan can be calculated to be in average 893 hrs/a x 100 W x 0.25ct/kWh = 22.3 €/a.

In conclusion, the results suggest that it is not the control itself, which leads to a higher acceptance of increased indoor temperatures in summer, but the effectiveness of the control. For the analysis of the performance tests, only minor differences in the performance under the distinctive conditions were observed.

Comfort votes and simulation suggest, that the installation of a ceiling fan does not only improve thermal comfort of occupants, but could be a cost effective measure resulting in a lower cooling demand. Further, building concepts using naturally ventilation will work in a wider range of climate conditions.

Acknowledgement

This project is funded by the German Federal Ministry of Economics and Technology (BMWi) with the project ID: 0327241C. The new test facility LOBSTER was funded by the German Federal Ministry of Economics and Technology (BMWi) with the project ID: 03ET1035B and supported by industrial partners. The authors are indebted to the Baden-Württemberg Stiftung for the financial support of this research project by the Eliteprogramme for Postdocs.

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