Proceedings of 7th Windsor Conference: ***The changing context of comfort in an unpredictable world*** Cumberland Lodge, Windsor, UK, 12-15 April 2012. London: Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

# Is there a method for understanding human reactions to climatic changes? – Developing experimental designs for climate chambers and field measurements to reveal further insights to adaptive processes

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**Abstract**
The adaptive comfort model states behavioural, physiological and psychological adaptive processes as reasons for the discrepancies between predicted mean vote and observed comfort votes. However, little is known about the individual portions of these processes. This paper presents a new experimental design which is meant for climate chambers with at least one façade connected to the exterior. This design consists of distinctive settings with respect to variations in outside conditions and the number of control opportunities so that one or more of the three adaptive processes are suppressed. Results of a trial analysis of the data gained through a first implementation of this experimental design in a climate are presented and discussed. One of the main results shows that the permission to interact with the built environment by means of using a fan or opening a window alone leads to a significantly increased satisfaction with the thermal conditions. This statement is supported by the regression lines of the comfort temperatures calculated according to the Griffith method.

**Keywords:**
Adaptive comfort, inside-outside climate chamber, neutral temperature, interaction

## 1 Introduction

Due to more and more observed unusual weather phenomena, there is an urgent need to identify and quantify the abilities of occupants to adapt to climate changes. The adaptive comfort model states behavioural, physiological and psychological adaptive processes as reasons for the discrepancies between predicted mean vote and observed comfort votes (Auliciems, 1981, deDear et al., 1997, Humphreys and Nicol, 1998).

Candido et al. (2012) showed that it is possible to investigate physiological adaptive processes in classical climate chambers. They investigated the effect of short-term artificially induced heat acclimatization on subjects' thermal and air movement preferences and found significant differences between the subject's votes before and after being forced to do daily exercises in hot and humid conditions.

Nevertheless, the other two processes are difficult to look at in a climate chamber setting. This is especially due to the lack of behavioural opportunities. On the other hand, field studies do in most cases not allow to control the thermal environment or to manipulate the number of behavioural opportunities.

To overcome this problem, an experimental design for climate chambers with at least one façade connected to the exterior was developed and implemented in a first series of measurements. This paper discusses the outcome of a trial analysis of the data gathered through this implementation. The trial analysis consists of two analysis procedures commonly used to analyse the observed thermal sensation votes obtained by small samples in field studies. This paper discusses the applicability of these procedures to data gathered in a semi-controlled climate chamber setting.

## 2 Development and implementation of the experimental design

In this paper only a short overview is given with regard to relevant aspects; for a detailed description see Schweiker et al. (2012).

### 2.1 Experimental settings

In order to reveal the individual adaptive processes, it is necessary to establish a methodology, which allows a detailed and statistically reliable analysis of each process individually and interacting with one or more of the other processes. Therefore, it would be meaningful to create conditions which suppress or enable one, two or all three of the adaptive process types. This would mean to block or enable behavioural interactions, have subjects physiologically adapted or not adapted to warm conditions and/or create conditions which are in congruence with the subjects' expectation or not.

The developed experimental design reacts to these requirements by means of six distinctive settings as presented in Table 1 and described in the following.

| | Interaction type | Outdoor conditions ($T_{rm}$) | Room conditions | Assumed level of short-term adaptation |
|---|---|---|---|---|
| 0- | i-[1)] | <20°C | Free running | Not adapted |
| 0+ | i+[2)] | <20°C | Free running | Not adapted |
| A- | i- | <20°C | Heated | Not adapted |
| A+ | i+ | <20°C | Heated | Not adapted |
| B- | i- | >20°C | Free running | Adapted |
| B+ | i+ | >20°C | Free running | Adapted |

[1)] i-: sessions without permitted interaction (windows closed, no sun shading, no fan)
[2)] i+: sessions with permitted interactions

*Table 1. Conditions during the sessions*

Conditions 0, A, and B refer to the assumed degree of short-term acclimation and thermal conditions inside the office cell. Fig. 1 shows a representation of the conditions with respect to the outdoor running mean and indoor operative temperature. The lines represent the acceptable conditions according to the categories I to III as defined in DIN EN 15251 (2007). The 0-condition was meant as baseline condition, where the subjects are not adapted to warm conditions and the office cell is neither cooled nor heated with indoor conditions being within the acceptable operative temperatures according to the adaptive comfort standard. In conditions A, the subjects are not adapted to warm conditions, but the office cell is heated by means of a ceiling panel without the subjects being informed about it. Compared to the acceptable conditions defined in DIN EN 15251 (2007) the operative temperatures are above those defined as acceptable for class I buildings. Conditions B refer to adapted subjects and an office cell, which is neither cooled nor heated. Due to higher outdoor temperatures the operative temperature indoors is higher than in conditions 0, but within the acceptable conditions defined in Ref. DIN EN 15251 (2007). The distinction between the conditions with adapted subjects and non-adapted subjects was based on a weighted running mean of the daily mean outdoor temperature (with alpha = 0.8) calculated according to DIN EN 15251 (2007). A running mean temperature below 20 °C refers to conditions 0, and A, while those above were sorted as condition B.

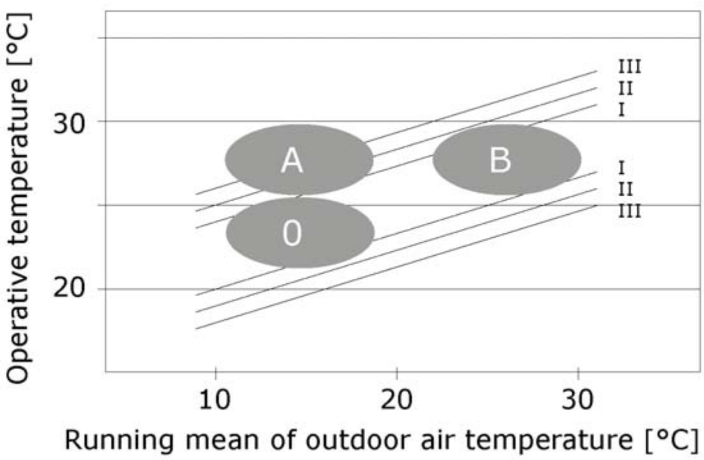


*Fig. 1. Graphical representation of the conditions as they were planned with respect to the outdoor running mean and indoor operative temperature. The lines represent the acceptable conditions according to the categories I to III as defined in DIN EN 15251 (2007).*

Conditions i+/i- refer to the degree, behavioural adaptation processes were permitted. In conditions i+, the subjects had the chance to adjust their clothes, open/close the window, move the external shading device and/or use a ceiling fan. In contrast, except for the adjustment of clothes, none of those actions was permitted in conditions i- and in addition, the level of clothing the subjects had to wear when entering the test facility in the morning was communicated to them before the respective session.

**2.2 Experimental procedure**

For the first experimental phase conducted between June and September 2010, 21 male students were chosen as subjects based on their health conditions of which 17 participated until the end of the experiments. Furthermore, they had to be younger than 31 years due to the higher probability of increased thermal expectations in this age group according to Bischof et al. (2002). All subjects were living in Germany for more than 3 years before the experiment. 15 of them are indigenous Germans; the other two were born and partly grew up in central-Asian countries which climate is categorized according to Koeppen-Geiger (Kottek et al., 2006) in category D, i.e. continental. The regression coefficients obtained by below described methodology for these two subjects were all within the normal range of all subjects, i.e. the were within the range of one standard deviation around the mean value of all subjects. Therefore, the data of these two subjects does not need to be dealt with separately.

The subjects were asked to work on their own during 8 non-consecutive days for 8 hrs (from 9 pm till around 4.30 pm with 30 min lunch break) in the test facility. Each of the six distinctive sessions introduced above had to be conducted once, in addition, sessions A+ and B+ were supposed to be conducted twice.

A computer based questionnaire as shown in Figure 2 was used to assess the thermal sensation vote, thermal preference, thermal acceptance, 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). This questionnaire was designed to pop up on the subjects' working screen every hour in the pattern shown in Figure 3.

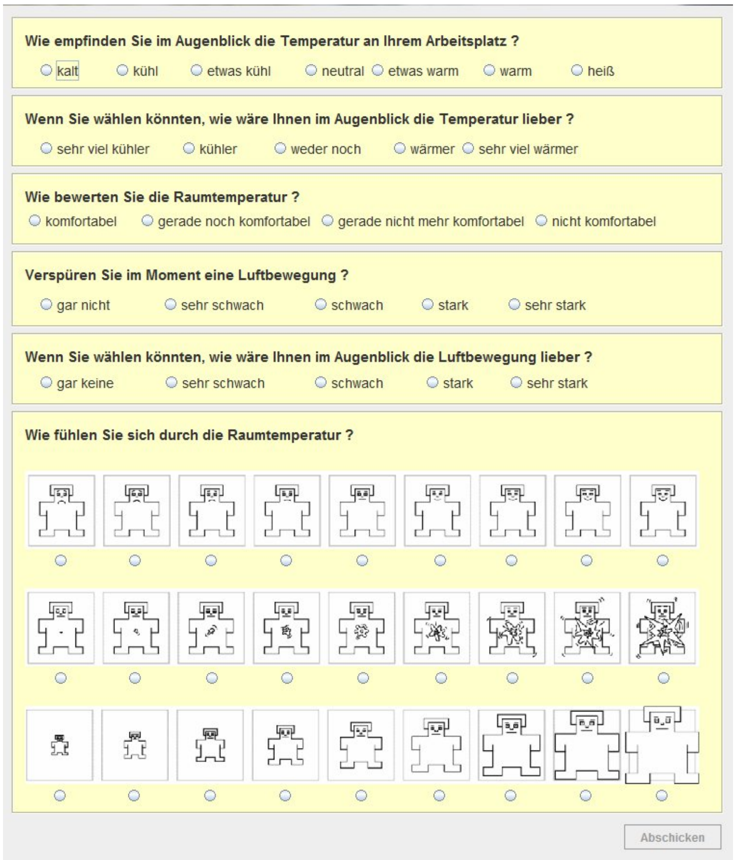


*Fig. 2. Computer-based questionnaire used during the experiments to assess thermal sensation, thermal preference, thermal acceptance, sensation of air movement, preference of air movement and three items related to the perceived levels of pleasure, arousal and dominance.*

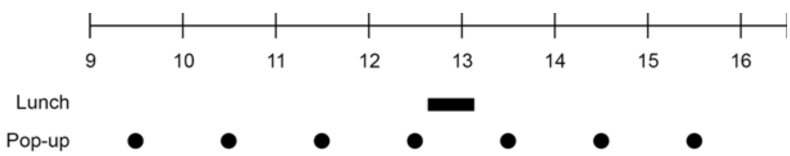


*Fig. 3. Schedule of the computer-based questionnaire*

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

**2.3 Test facility**

The experiments were conducted in a prefab concrete building cell with the size of one office unit situated at the University Wuppertal. The so-called btga-box is placed on a 60 cm high base of insulation boards and all external faces except the south-facing one are well insulated. The south-facing front consists of a post and beam construction made of insulated aluminium profiles.

In addition to the possibility to open one or both of the windows, the ventilation concept involves the outdoor air diffuser elements which provide the room with fresh air either passively due to a negative pressure inside the box or actively by means of an integrated fan. The whole of the glass surface can be shaded by one electrically driven external shading device which provides daylight through the upper part even when closed. The control of the shading device was done by a wireless-switch placed in the middle of the two tables. The indoor temperature could be artificially decreased or increased by means of a ceiling panel. The control of the ceiling panel was not in the hands of the subjects – in fact, they were not told that such panel exists.

**3 Analysis methods**

As presented in Fig. 4, the conditions during the sessions with respect to operative temperature and running mean outdoor temperature could not be set as planned (compare Fig. 1); the thermal conditions were partly overlapping. This was especially the case for conditions 0+ and A+, which is mainly due to the few control opportunities of the inside conditions. As a consequence, the comfort votes received in each of the six session types cannot be compared without considering the thermal conditions in the moment they were given. Therefore, two approaches, commonly considered for the analysis of small samples deriving from field studies (see e.g. Indraganti, 2010) were tested with respect to their suitability in revealing new insights into the individual adaptive processes. These approaches allow the comparison of the six session types while reflecting at least the differences in operative temperatures and will be described below.

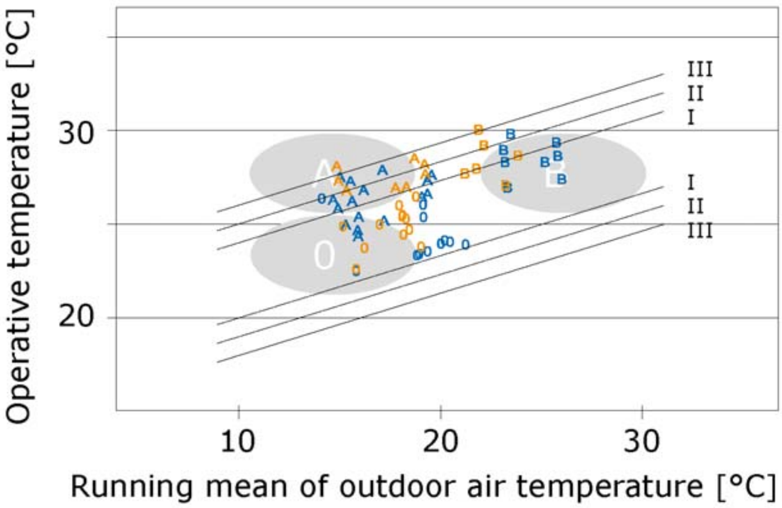


*Fig. 4. Mean operative temperature during the sessions in relation to the outdoor running mean and indoor operative temperature. The lines represent the acceptable conditions according to the categories I to III as defined in DIN EN 15251 (2007). Blue characters represent the values observed during i+ sessions, orange characters the ones observed during i- sessions.*

In contrast to the indoor conditions, there is a clear difference between sessions 0/A and B with respect to the running mean outdoor temperature. Therefore, the session type can serve as a meaningful representation of the degree of acclimatization.

For the first approach, mentioned above, a linear regression of the thermal sensation vote (TSV) upon the operative temperature, $T_o$, at the moment of the vote was performed as described in de Dear et al. (1997). This analysis was done for (1) all data, (2) subsets containing the data of each session and (3) for subsets of the data divided into conditions i- and i+. The values for the coefficient, a, and the constant, b, obtained by the regression analysis were then used to calculate the neutral temperatures, $T_n$, and the comfort band (TSV from -1 to +1) based on the relationship

$$T_n = (TSV + b) / a, \quad (1)$$

with TSV set to be 0 for the neutral temperature and to -1 and +1 for the comfort band.

In the second approach, the neutral temperature by Griffith' method (Griffith, 1990), $T_{nG}$, was calculated for each vote. The Griffiths' method was developed for small sample sizes in order to overcome poor correlations found in field studies, where the TSV is seldom dependant on the operative temperature alone.

In this study the modifications described by Rijal et al. (2008) were applied, which gives the neutral temperature to be

$$T_{nG} = T_g + (0 – TSV) / R, \quad (2)$$

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. Please note that the letter R used here has nothing in common with the later discussed $R^2$-value. $T_g$ is used as an approximation to operative temperature in their study, so that $T_o$ could be used for this study without problems.

Different values for R were considered. First, $R_1$ was set to be 0.33, which is related to the finding of Fanger (1972) that, all else being equal, the comfort vote increases by one unit for each three degree rise in globe temperature. Second, a value ($R_2$) of 0.5 was used as obtained by Rijal et al. (2008) for field studies in Pakistan. Third, the regression coefficient ($R_3$) obtained through above mentioned regression analysis of all data was taken. Finally, for each subject an individual regression coefficient ($R_4$) was calculated based on all votes given during all sessions and applied to the respective votes.

For all analyses, the first vote of each day was not considered, due to a possible influence of different transport means (bicycle, train, car) on the metabolism.

## 4 Results and discussion

The total number of votes given in each session is shown in the first column of Table 2. The low number of votes for the B-sessions is due to a much shorter warm period in the summer 2010 than expected. Therefore, some of the subjects could not perform their B-sessions.

| Data (subset) | N | $T_{rm}$ [°C] | $T_{op}$ [°C] | RH [%] | A [m/s] |
|---|---|---|---|---|---|
| all | 871 | 18.7 (8.5) | 26.4 (5.9) | 43 (78) | 0.07 (.003) |
| i- | 371 | 18.3 (5.9) | 27.4 (5.6) | 42 (61) | 0.07 (0.002) |
| i+ | 500 | 19.1 (10.5) | 25.9 (5.8) | 44 (87) | 0.07 (0.003) |
| 0- | 152 | 18.1 (1.3) | 25.5 (5.0) | 45 (50) | 0.09 (0.003) |
| 0+ | 166 | 19.2 (4.3) | 24.3 (2.9) | 53 (65) | 0.07 (0.002) |
| A- | 130 | 18.3 (3.4) | 28 (2.6) | 36 (52) | 0.05 (0.001) |
| A+ | 246 | 16 (2.9) | 26.1 (2.7) | 43 (61) | 0.07 (0.003) |
| B- | 89 | 21.9 (0.7) | 28.7 (3.2) | 43 (47) | 0.09 (0.001) |
| B+ | 88 | 23.6 (1.5) | 29 (4.6) | 37 (42) | 0.11 (0.007) |

*Table 2. Number of votes, mean values and variances of running mean outdoor temperature, $T_{rm}$, operative temperature, $T_{op}$, relative humidity, RH, and air velocity, A, for each subset of data*

The mean values and variances of running mean outdoor temperature, $T_{rm}$, operative temperature, $T_{op}$, relative humidity, RH, and air velocity, A, are presented in the following columns of Table 2. The mean $T_{rm}$'s of the B sessions are 2 to 7K higher compared to the other sessions. The mean $T_{rm}$, is higher in session B+ compared to A+ due to cooler outdoor air entering the room during the A+ sessions and the lack of heat source to counterbalance this heat flow as mentioned above. Mean relative humidity and air velocity are comparable in all session types.

**4.1 Neutral temperatures based on regression analysis**

Table 3 presents the regression coefficients, their standard errors and the resulting neutral temperature, $T_n$, for the analyzed cases.

The slope of the regression line (a) for all data (0.23) is much lower than that found e.g. by Fanger (1972) (0.33), Rijal et al. (2008) (0.5) or Indraganti (2010) (0.31). This indicates that the subjects' votes are less affected by changes of the indoor temperatures, which can be confirmed by the wide comfort range from 18.8°C to 27.6°C.

Comparing the regression coefficients for the data of all i- sessions (without behavioural interaction) with those of the i+ sessions, the latter is even lower than stated above. This results in a comfort temperature, $T_n$, being more than 3K lower for the i- sessions and a comfort range being 6K narrower. This shows the dramatic effect of higher acceptance due to a higher (perceived) level of control. Such effect, observed by other studies (e.g. Brager et al., 2004 or Hellwig et al, 2006) could now be quantified.

The following rows in Table 3 confirm the just stated difference between the i- and the i+ sessions for each condition 0, A, and B. In addition, the results suggest, that there is no increased neutral temperature in condition B as one would have expected based on the hypothesis that there is physiological adaptation due to higher outdoor temperatures. In contrast, the neutral temperatures in condition B- and B+ are even lower than those in the respective 0 and A conditions.

The extreme comfort range for condition 0+ can be explained with the high number (144 of 166) and percentage (87%) of votes being "neutral" during these conditions.

| Data (subset) | a | | | b | | | $R^2$ | $T_n$ | Comfort range | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| All | 0.228 | ± | 0.011 | -5.30 | ± | 0.293 | 0.33 | 23.2 | 18.8 | - | 27.6 |
| i- | 0.245 | ± | 0.015 | -5.22 | ± | 0.414 | 0.41 | 21.3 | 17.2 | - | 25.4 |
| i+ | 0.147 | ± | 0.010 | -3.62 | ± | 0.273 | 0.29 | 24.6 | 17.8 | - | 31.4 |
| 0- | 0.287 | ± | 0.025 | -6.24 | ± | 0.643 | 0.46 | 21.7 | 18.3 | - | 25.2 |
| 0+ | 0.014 | ± | 0.021 | -0.39 | ± | 0.521 | 0.00 | 27.9 | -43.5 | - | 99.4 |
| A- | 0.230 | ± | 0.038 | -4.88 | ± | 1.059 | 0.22 | 21.2 | 16.9 | - | 25.6 |
| A+ | 0.116 | ± | 0.021 | -2.91 | ± | 0.539 | 0.12 | 25.1 | 16.4 | - | 33.7 |
| B- | 0.203 | ± | 0.040 | -3.98 | ± | 1.153 | 0.23 | 19.6 | 14.7 | - | 24.5 |
| B+ | 0.188 | ± | 0.031 | -4.52 | ± | 0.907 | 0.30 | 24.1 | 18.7 | - | 29.4 |

*Table 3. Regression coefficients (a: slope, b: intercept) and their standard errors, $R^2$-values of the regression model, neutral temperatures, $T_n$, and comfort ranges for each subset of data.*

The $R^2$-values of the i- sessions and the 0- sessions with values around 0.4 are comparable to those found in other field studies (see e.g. Indraganti, 2010). The others, especially those of the sessions with an increased number of interactive opportunities (the (i)+ sessions) signify that there are other factors than the operative temperature leading to a high variance in the data. As shown in Table 2, the air velocity is most probably not such factor due to its low variance. Further analysis of the data together with further experiments are meaningful in order to extract those factors from the data.

### 4.2 Neutral temperatures based on Griffith' method

The mean neutral temperatures based on Griffiths' method are shown in Figure 5 for each subset of data and chosen regression coefficient ($R_1$ to $R_4$).

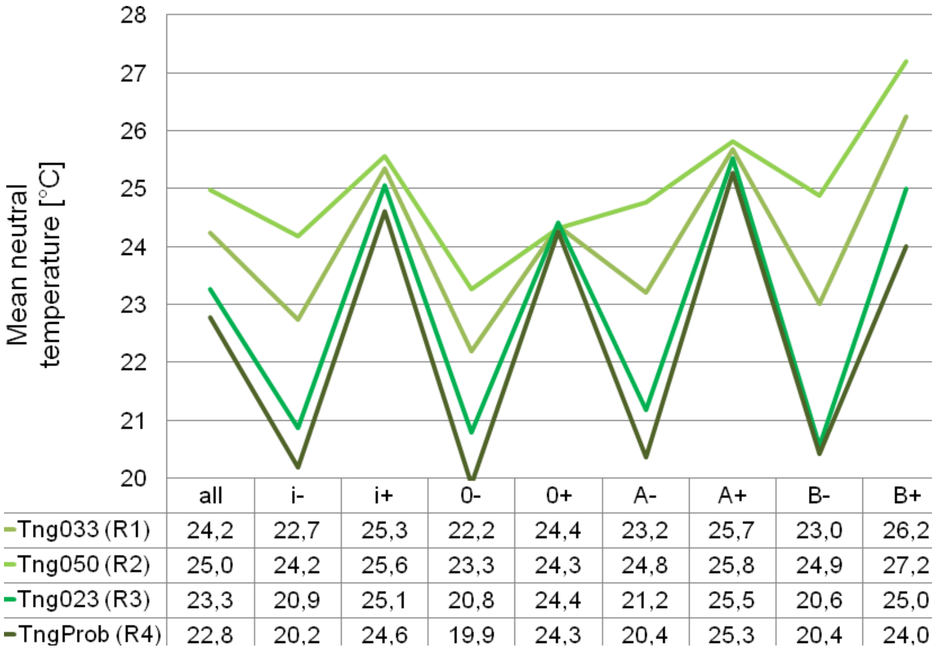


*Fig. 4. Mean neutral temperatures based on Griffiths' method, $T_{nG}$, for each subset and chosen regression coefficient (R).*

In general, the same tendency between i- and i+ sessions can be observed; the neutral temperatures are 2K to 4K higher, when the subjects had a higher degree of control over their indoor environment.

In contrast to the outcome of the neutral temperatures based on the linear regression analyses, the neutral temperature based on Griffiths' method is increasing from session type 0 over A to B in case of R being .33 ($R_1$) or .5 ($R_2$). For $R_3$ and the i-sessions, type B has the lowest neutral temperature, while for the i+ sessions, type A has the highest neutral temperature, followed by B. Looking at $R_4$, the differences in neutral temperatures between the i- sessions and the i+ sessions is at its maximum. Again, the mean neutral temperature for session B+ is lower than that for sessions 0+ and A+.

These results show, that the decision for a certain value of R used for the adjusted Griffiths' method has a strong influence on the outcome of such comparison. This is in particular true for the comparison of the mean neutral temperatures of sessions A+ and B+. With the hypothesis, that an increased running mean outdoor temperature leads to an increased neutral temperature, one would expect a higher neutral temperature for the B+ sessions compared to the A+ session. Nevertheless, such relationship can be found when using $R_1$ or $R_2$, but not with $R_3$ or $R_4$. Further research and analyses would be meaningful to determine if possible a general applicable value for R, when using the Griffiths' method.

## 5 Conclusions

A new experimental design was introduced, which is suitable for a climate chamber having at least one window facing to the exterior. This design consists of six distinctive settings, separated through the level of control and physiological adaptation. It was shown that this type of climate chamber enables experiments, which deal with behavioural and physiological aspects of adaptation.

The applicability was further demonstrated and the data gathered through this application was analysed with respect to differences in neutral temperatures between the distinctive session types. One of the main results shows that the permission to interact with the built environment by means of using a fan or opening a window alone leads to a significantly increased neutral temperature and a wider comfort range. These statements are supported by the comfort temperatures calculated according to the Griffiths' method.

In contrast, there was no significant difference in the neutral temperatures between the conditions with lower running mean outdoor temperature (session types 0, A) and higher values (B).

Nevertheless, the chosen regression coefficient to calculate the neutral temperature had a significant influence on the outcome. Further research to determine a suitable value is therefore proposed.

In conclusion, the first overview of the data gathered through the developed experimental design shows the ability to analyse the adaptive processes individually. Such ability looks promising in order to reveal the single effects leading to the phenomenon called adaptive comfort, which can help understanding necessary measures to prepare existing and new buildings for an unpredictable world.

**Acknowledgement**
This project is funded by the German Federal Ministry of Economics and Technology (BMWi) with the project ID: 0327241C.

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