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PERSONAL CONTROL OVER TEMPERATURE IN WINTER IN DUTCH OFFICE BUILDINGS

Abstract

A field study was conducted during heating season in nine modern office buildings in the Netherlands.
A first objective of the study was to investigate what kind of control Dutch office workers have over temperature in winter (available control), to map how often these controls are used (exercised control) and to identify how much control the office workers perceive to have over temperature in winter (perceived control). A second objective was to objectify the amount of control over temperature in winter with thermostat effectiveness measurements. The third objective was to investigate how available control and exercised control impacts the level of control over indoor climate in winter as experienced by office workers (perceived control). The study consisted of (i) a systematic inventory of relevant building and HVAC system characteristics, (ii) a questionnaire amongst building occupants and (iii) indoor climate measurements. Concerning the latter: to evaluate the effectiveness of controls dynamic experiments have been performed. These experiments consisted of manual adjustments of thermostats by the researchers. After these interventions response times and step responses for room temperature were identified to quantify how effective controls were in changing room temperature.
The outcomes of the study can be used to improve temperature control in existing and new office buildings.

Introduction

Several studies have shown that having or not having control over one's indoor climate affects how that indoor climate is perceived (Bell et al, 2002; Boerstra, Beuker, Loomans & Hensen, 2013). There is growing evidence that human responses to sensory stimuli such as suboptimal temperatures modify when those exposed have control over these stimuli, i.e. when building users have adaptive opportunities (Brager & DeDear, 1998).

In this context Rohles (2007) mentions that personal preferences differ a lot, therefore the ability of an individual to control his or her environment does have a considerable effect on satisfaction with the surroundings.

Bordass, Leaman & Ruyssevelt (2001) conducted the so-called Probe study in the UK. One clear conclusion from that study was that occupants like buildings that can respond to them. According to the authors people are most comfortable, healthy and productive in buildings that have operable windows and effective and usable temperature controls.

Nicol & Humphreys (1973) and Paciuk (1990) arrived at similar conclusions. These results support the hypothesis that feedback loops for personal control should be taken into account when assessing and designing indoor climates.

Modern Dutch office buildings typically have several control options. Especially operable windows and adjustable thermostats are quite common. Sometimes, in the case of single person rooms, these controls offer individual control. Often these controls are shared with others, for example in the case of office landscapes. A lot is still unclear about control over indoor climate in Dutch offices. Unanswered questions are for example: How effective are adjustable thermostats and other controls? How fast does the temperature change when you use the controls? How often do people use their controls? And how does having or not having control and the frequency of control use affect the perceived level of control over one's thermal environment? And how does the quality of indoor climate controls and their effectiveness affect perceived control over temperature?

A field study was designed to answer the above questions and to further study personal control over indoor climate in Dutch office buildings. Central aspects to investigate were (with reference to Paciuk (1990)): available control, exercised control and perceived control. In this paper the results related to control over temperature in winter (thermal environment in winter) are presented.

The first objective of the field study was to find out how much control Dutch office workers have over temperature in winter, to map how often their winter controls are used and to identify how much control the office workers perceive to have over temperature in winter. A second objective was to objectify the amount of control over temperature in winter through thermostat effectiveness measurements. The third objective was to investigate how available control (access to controls) and exercised control (frequency of use of controls) impacts perceived control over indoor climate in winter.

Methods

The field study was carried out in nine office buildings located in different cities in the Netherlands.

The buildings were selected based on the following criteria:

- State-of-the art office work environment (relatively modern office concept);
- Well maintained building and HVAC systems;
- Gross net floor surface at least 2,000 m^2 (around 22,000 ft^2);
- Easy access for the research team to the workspaces (and the office workers).

The selected buildings were used by either governmental institutions or commercial organizations. The buildings were equipped with different types of HVAC systems ranging from traditional to more innovative systems such as slab heating/cooling systems.

Note that Dutch office buildings differ in an important way to average office buildings in North-America and Asia: they normally have more options for control. Eight of the nine buildings studied had operable windows and seven buildings offered possibilities for manual temperature control in winter at room level.

The buildings were visited at different times between November 2011 and March 2012. Average maximum outside temperatures during winter in the Netherlands normally lie at around 3 to 6 °C (37 - 43°F).

Inside the buildings relevant building and HVAC system characteristics were mapped with the use of a checklist. For example, an inventory was made of the kind of heating systems that were installed in the buildings and of the ways these heating systems could be controlled by the building occupants. A more detailed description of the nine buildings can be found in Table 1.

[INCLUDE TABLE 1 AROUND HERE SOMEWHERE]

Also building occupants' perceptions were mapped. In each building between 20 and 30 people were asked by the lead researcher to manually fill in a questionnaire. The total number of respondents for the nine buildings was 236. The respondents were selected at random. Purposely we looked for respondents spread out over different floors, different departments, different facades etc. The response rate was > 95%: more or less everybody that was approached agreed to fill in the questionnaire. After the respondents filled in the questionnaire they were asked to participate in an extra 10 minute face-to-face interview. A total of 161 building occupants agreed to participate in this part of the research.

In each building also several measurements were conducted (on average 10-15 per building). These interventions consisted of an active control action by the researchers. Most interventions were upward adjustments of adjustable thermostats or downward adjustments of thermostats. Sometimes also other controls, like operable windows and blinds were tested (no further results of these non-thermostat experiments are presented in this paper).

The interventions and their follow-up measurements were meant to objectify the available level of control that occupants had over the indoor climate in winter. The measurement outcomes were used to quantify the effectiveness of controls, especially adjustable thermostats. For more information see the separate text box 'thermostat effectiveness measurement procedure'. The main assumption here was that in an ideal winter scenario with good control options building occupants are able to control the operative temperature at their workstation with adequate speed, within a bandwidth of at least 20- 24 °C (68-75 °F), in accordance with the PMV = +0.5 and PMV = -0.5 limits for heating season as mentioned in ISO 7730 and ASHRAE standard 55.

Than as far as the data analysis is concerned:

The outcomes of the inventory, questionnaires, interviews and interventions were compared to investigate correlations between available control, exercised control and perceived control.

In this context the following information was used:

For available control: 1. access to an adjustable thermostat, 2. access to an operable window, 3. limitations on control use as enforced by building manager, and 4. measured upward thermostat speed; The first three aspects were derived from the questionnaire / interview outcomes. The fourth aspect was obtained from the intervention experiments.

For exercised control: 1. frequency of use of adjustable thermostats (in winter), 2. frequency of use of operable window (in winter), and 3. frequency of clothing adjustments (in winter); All three aspect were derived from the questionnaire / interview outcomes.

For perceived control: 1. perceived control over temperature in winter, 2. perceived control over ventilation, 3. perceived control over air velocity and 4. perceived thermostat speed (in winter). These aspects were derived from the questionnaire / interview outcomes. The fourth aspect, perceived thermostat speed, furthermore was compared to the *measured* average thermostat speed in the building.

Correlations between available, exercised and perceived control were investigated with the statistical program SPSS 20. Specific tests used were: the Mann Whitney U test, Pearson's product-moment correlation and Spearman's rank correlation. The tests used were selected based on the methodological recommendations presented in Baarda, De Goede & van Dijkum (2011) and Baarda & de Goede (2006).

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THERMOSTAT EFFECTIVENESS MEASUREMENT PROCEDURE

The thermostat effectiveness measurement procedure consisted of 4 steps:

Step 1 ‘Room selection’:

Upon arrival in each building a walk through survey was conducted. Indicative measurements with handheld devices of the actual room conditions (especially air temperature, relative humidity and CO_2 concentration) were used to identify suitable rooms to perform an intervention experiment in. For example, rooms with a relatively low air temperature (around 21 °C / 70 °F or lower) in which an adjustable thermostat could be readjusted by the researchers from a low setting (‘0’ on a 0-5 scale) to a high setting (‘5’ on the 0-5 scale). Or rooms with a relatively high air temperature (around 23 °C / 73 °F or higher) in which an adjustable thermostat could be readjusted from a high to a low setting. Selected rooms were expected not to have substantial changes in terms of external and internal heat loads during the first 2-3 hours after the thermostat setting was changed. This meant that for example rooms on the West side were selected for experiments during the morning and rooms on the East side were selected for afternoon experiments (in both cases to avoid temperature disturbances from changes in solar energy influx in the rooms).

Step 2. ‘Start intervention’:

Next the measurement equipment was installed in the selected rooms. For the measurements a calibrated Brüel & Kjær 1213 climate analyzer was used and several calibrated CaTeC klimabox 5000 logging devices (measurement accuracy for air temperature: 0.2 and 0.3 °C or 0.36 an 0.54 °F). The measurement equipment was placed as close as possible to one of the workstations in the room, at table height (around 0.7 - 1 m above floor level). The main focus was on (changes in) air temperature (not operative temperature or radiant temperature). Nevertheless, at the start and end of each intervention (see below) control measurements (with the Brüel & Kjær 1213) were made to check for any unusual changes in radiant temperature and relative humidity during the experiment. After an acclimatization period of 15 minutes the actual intervention was performed, i.e. one of the researchers readjusted an adjustable thermostat from a low setting to a high setting or vice versa.

Step 3. ‘End intervention’:

At intervals of about 30 minutes, handheld devices were used to determine whether and how air temperature and other indoor climate aspects had changed since t_0. During these inspection rounds it was also assured that no major changes in terms of ‘loading’ of the rooms had taken place. For example because some of the occupants had left the room for longer periods of time. In the rare situations that this was the case, the experiment was cancelled. As soon as a new steady state was reached in a room (this varied and sometimes lasted more than 3 hours) the intervention was stopped (at t_{end}) after which the measurement data were retrieved for further analyses. Next the thermostat was put back to the original setting (as at t_0).

Step 4. ‘Measurement data analysis’:

Each intervention was quantified in terms of step response and response time. These terms are graphically explained in Figure 1. Step response is defined as the difference between the measured value (air temperature) at the new steady state conditions and the value at t_0. The response time is defined as the time interval between t_0 and the time t_{end} at which the new steady state has been reached. Also the concept of half-life is explained in Figure 1. Half-life ($t_{½}$) is the time interval after which the measured value (in this case air temperature) is equal to $T(t_0)$ plus 0.5·times the step response. Half-life is a general concept that is also used in other fields (chemistry, physics, biology, etc.) to describe any phenomenon which follows an exponential change in time. The prime indicator that is calculated is ‘thermostat speed’ (in Kelvin per minute or Kelvin per hour). This refers to (an approximation of) the average rate at which the temperature changes during the time interval t_0 to $t_{½}$. The thermostat speed is calculated by deviding 0.5·times the step response with ($t_{½}$ -t_0). See again Figure 1.

[INCLUDE FIGURE 1 ABOUT HERE AS INTEGRAL PART OF THE TEXT BOX]

[END OF SEPARATE TEXT BOX]

Results and discussion

In the next sections the results are presented and discussed. First (see ‘Part 1’) the questionnaire and interview outcomes and descriptive results related to available and exercised control are presented. Than the intervention outcomes for the thermostat effectiveness measurements are described (under ‘Part 2’). The third results section (see ‘Part 3’) focuses on correlations between available control, exercised control, measured control effectiveness and perceived control.

Part 1: Questionnaire and interview outcomes

Available control - general

Of the respondents that participated in the interviews 70% indicated they had access to a thermostat for temperature adjustment in winter. In most cases this was an adjustable wall thermostat or an adjustable thermostatic valve on a radiator or convector; 87% indicated they had access to an operable window. Other examples of controls that people indicated having were: blinds (inside and outside), electrical heaters and table fans (the latter mainly for ‘summer use’). As far as blinds are concerned: these appeared mainly to be used in summer and/or at moments that people experienced visual discomfort. Therefore, this aspect is not addressed further in this paper.
As far as organizational norms and available control is concerned: 34% of the interviewees indicated that their facility manager has imposed restrictions on the use of controls (a ‘ban’ on the use of adjustable thermostats and/or operable windows).

Exercised control - frequency of control use

Those that participated in the interviews were asked how often they use their ‘winter controls’. The resulst are presented in table 2. Only 21% use adjustable thermostats on a daily or weekly basis in winter; 43% use an operable window daily or weekly during the heating season, while 49% make clothing adjustments (in reaction to a suboptimal thermal environment) on a daily or weekly basis during the winter season. These results show that adjustable thermostats are used less often in winter than operable windows and adaptation through clothing adjustment.

There is a significant difference between man and women in the use of thermostats during heating season. Men use thermostats less frequent than women ($Chi^2 = 11.9$; df = 4; p (2 sided) = 0.018). No significant difference between men and women in the use of operable windows in winter was found. As far as clothing adjustments in winter are concerned: men do this significantly less often than women ($Chi^2 = 9.2$; df = 3; p (2 sided) = 0.026). Overall, men are more passive and use their winter controls less often than women.

[INSERT TABLE 2 AROUND HERE]

Exercised control – standard reactions when cold

During the interviews the participants were asked how they normally react (at their workplace) when they are cold. They had the possibility to name one or more standard (re)actions (up to three in total). Of the 161 respondents, 45 said never to experience that situation (never being cold at work). Of the remaining 116 16% indicated to normally react, when cold, by adjusting their thermostat only (no other actions); and 27% indicated using their thermostat, when cold, in combination with other actions which brings the total for thermostat adjustment as a standard reaction to being cold on 43%. This means that 57% of the respondents do *not* use a thermostat when cold but will resort to other actions (one or more). These included: adding extra clothing (putting on a sweater, shawl etc.), raising metabolism (taking a walk through the building to become warm again) and taking a hot drink.

Several respondents also mentioned resorting to internal coping (just accepting that it is cold at certain moments and just to wait until it gets warmer). In Table 3 the incidence of standard reactions is presented. The ‘other’ score in Table 3 refers to (re)actions like walking away to a warmer room, plugging in one’s own electrical heater, closing windows or doors, closing or opening blinds or curtains, putting clothing or other things in/on air inlets, going home earlier, and sitting on one’s hand.

[INSERT TABLE 3 AROUND HERE]

Exercised control – energy use awareness impact

Those that were interviewed were asked whether they take energy use effects into account when using adjustable thermostats and other controls. A total of 82% said they did *not* take energy use into account when (re)adjusting thermostats and when using other indoor climate controls like operable windows. The respondents were asked why they normally do not think about energy use effects. Some example responses:

- *‘Comfort is more important at the workplace than energy use, therefore I never think about energy effects when changing the temperature or opening a window.’*
- *‘At home off course I do think about energy effects when adjusting the thermostat, but no, never at my workplace. Probably this has something to do with the fact that at home I pay the energy bill myself.’*
- *‘When I leave my office I always shut off my computer and switch off the light, but guess with heating I never think about the energy-effect therefore never readjust the wall thermostat when leaving the room.’*
- *‘Energy use is of secondary importance at work; most important is that I feel good.’*

Perceived control – general satisfaction

The respondents that participated in the interviews were also asked whether in general they are satisfied with the amount of control they have over their indoor climate: 31% answered ‘yes’, 38% answered ‘no’ and the remainder (31%) said ‘not yes, not no’.
In addition the respondents were asked to explain *why* they were satisfied or dissatisfied with the amount of control. Those that answered ‘yes’ (those that were satisfied) had explanations like:
- *‘I can adjust the heating, open a window and open or close blinds so overall I am very satisfied with the indoor climate.’*
- *‘I work alone in a private office therefore I can control everything quite all right.’*
- *‘There is no possibility to control the temperature, nevertheless I am satisfied with the amount of control as it normally is never too hot or too cold here.’*

Respondents that indicated *not* being satisfied with the amount of control gave the following types of explanations:

- *‘It’s often cold here and there’s nothing you can do about it.’*
- *‘It would be nicer if everyone for him/herself could adjust the temperature.’*
- *‘The temperature in winter can be adjusted yes, but personally I would prefer to have a wall thermostat as I have at home because that works much better and faster than this one here.’*

Further analyses of the answers to the open-ended questions revealed that there are large individual differences. Some do not seem to be interested in having control over their indoor climate (and are satisfied with the level of control anyway). Their experience is that their indoor climate normally is good anyhow without periodical (manual) adjustment of the indoor climate. In the words of one of the respondents: *‘The indoor climate is OK here so I do not need control over it; because of that I hardly* *ever use my thermostat and operable window…'* While others indicated that they can only be satisfied with the amount of control if they themselves are in charge and when adequate options for effective control are offered. In this context, one respondent indicated: '*It is all about how much control over the indoor climate you really want; this differs from person to person'*.

Perceived control - 7 point scale scores

The respondents furthermore were asked to indicate on a 7-point scale (with 1 = no control whatsoever and 7 = full control) what level of control they perceive to have over temperature in winter, ventilation and air velocity. The results are presented in Table 4. For comparison the results from the questions on control over temperature in summer, sun penetration, light and sound are included as well.

[INSERT TABLE 4 AROUND HERE]

Table 4 shows that the perceived level of control over temperature in winter is more than one point lower than for example the perceived level of control over sun penetration and light. Perceived control over air velocity is rated lowest of all.

With respect to perceived control no clear differences were found between men and women (Table 5). The only exception was perceived control over temperature in winter. Here men scored significantly lower (spearman's rho -0.111, p=0.045 with 1-tailed test) than women. The mean score of the men was 3.06 on the 7 points scale (mode was: 1.5), while the mean score for women was 3.44 (with mode of 5).

The number of persons that an office worker shares his workroom with (officemates) impacts perceived control (Table 5). There is a significant (negative) correlation between the number of officemates and the perceived level of control over temperature in winter (spearman's rho -0.375, p=0.000 with 1-tailed test). The relation is presented in more detail in Figure 2. The figure shows that the more persons one shares a room with, the lower the perceived level of control over temperature is. The number of officemates also has a significant negative effect on perceived control over ventilation, sun penetration, light and sound.

[INSERT TABLE 5 AROUND HERE]

[INSERT FIGURE 2 AROUND HERE]

The self-estimated distance between one's workstation and the facade also was significantly correlated with some of the perceived control levels (see Table 5). For example, there is a significant (negative) correlation between the distance and the perceived level of control over temperature in winter (spearman's rho -0.243, p=0,000 with 1-tailed test). This means that those that sit farther away from the façade do perceive having less control over temperature in winter. The distance between one's workstation and the facade also had a significant negative effect on perceived control over temperature in summer, ventilation, sun penetration, light and sound.

Part 2: Thermostat effectiveness measurement outcomes

Some examples of the thermostat effectiveness measurement outcomes are presented graphically in Figures 3 through 7. Figures 3 through 5 present the results of 'upward experiments' (where thermostats were adjusted from a low setting to a high one with the intention to increase the room temperature). Figures 6 and 7 present the results of 'downward experiments' (where thermostats were adjusted from a high setting to a low one with the intention to decrease the room temperature).

[INSERT FIGURES 3,4,5,6 AND 7 ABOUT HERE]

The results for all upward thermostat effectiveness measurements are summarized in Table 6. The results of the downward experiments are summarized in Table 7.

The two tables show that large differences between buildings can be found. For example, with the upward experiments, sometimes hardly anything happens when thermostats are adjusted (average thermostat speed +0.2 Kelvin per hour) while in other buildings air temperature changes relatively rapidly after adjustment of the thermostat (average thermostat speed +2.5 Kelvin per hour). Furthermore, upward adjustments of thermostats generally were more effective than downward adjustments (compare last columns of the two tables with each other). In some buildings downward adjustments resulted in contradictive outcomes as a temperature *increase* was measured while the intention was to *decrease* the temperature.

[INSERT TABLE 6 AND 7 ABOUT HERE]

Part 3: Correlation outcomes

The third objective of the field study was to investigate how available control and exercised control impact perceived control over indoor climate in winter.

Link between available control and perceived control

Those that do not have access to an adjustable thermostat score lower on perceived control over temperature in winter (Figure 8). The difference is statistically significant (Mann-Whitney U-test; mean rank respondents without thermostats is 55.29, mean rank for those with thermostats is 91.92; Z= -4.645; p= 0.000 (2-tailed)). Access to adjustable thermostats also has a significant (positive) correlation with perceived control over ventilation (mean rank resp. 65.61 and 87.54 ; Z= -2.794; p= 0.005 (2-tailed)) but it does not correlate with perceived control over air velocity.
These outcomes imply that that people working in office spaces that have adjustable thermostats generally perceive to be more in control over temperature in winter and over ventilation.

[INSERT FIGURES 8 AND 9 ABOUT HERE]

Access to operable windows does not have a significant effect on perceived control over temperature in winter. On the other hand: those that do not have access to an operable window score lower on perceived control over ventilation than those that do have access (Figure 9). This difference is significant (Mann-Whitney U-test; mean rank respondents without operable windows is 39.85, mean rank for those with operable windows is 85.78; Z=-4.269; p = 0.000 (2-tailed)). Access to operable windows also has a significant (positive) effect on perceived control over air velocity (mean rank resp. 75.18 and 81.09; Z=-2.412; p=0.016 (2-tailed)).
This implies that persons working in office spaces with operable windows generally feel more in control over ventilation and air velocity, but not over temperature in winter. Further analysis of the data showed that access to operable windows was also positively correlated with perceived control over temperature in *summer*.

Organizational restrictions on the use of controls do affect all three perceived control indicators.Those that indicated to experience restrictions on the use of controls score significantly lower on perceived control over temperature in winter (Mann-Whitney U-test; mean rank respondents without restrictions

is 77.86, mean rank for those with restrictions is 51.47; Z=-3.742; p = 0.000 (2-tailed)). The same holds for perceived control over ventilation (mean rank respondents without restrictions is 74.45, mean rank for those with restrictions is 58.23; Z=-2.305; p = 0.021 (2-tailed)) and for perceived control over air velocity (mean rank respondents without restrictions is 72.56, mean rank for those with restrictions is 56.13; Z=-2.497; p = 0.013 (2-tailed)).
The implication here is that if office buildings have adjustable thermostats, operable windows and other (winter) controls while people are not allowed to use them the perceived level of control in those buildings is lower than in buildings with unrestricted use of the (winter) controls.

Link between exercised control and perceived control

The impact of exercised control on perceived control is presented in Table 8. The analysis shows that there is a significant and strong correlation between frequency of use of adjustable thermostats in winter and perceived control over temperature in winter (Spearman's rho = -0.456; p= 0.000 (1-tailed)). Those that use their thermostats less frequent than monthly or never score significant lower on perceived control over temperature in winter. Perceived control levels over temperature in winter for those that use their thermostats daily, weekly or monthly however are comparable (Figure 10).
The frequency of operable window use is significantly correlated with not just perceived control over ventilation (Spearman's rho = -0.380; p= 0.000 (1-tailed)), but also with perceived control over temperature in winter (Spearman's rho = -0.197; p= 0.007 (1-tailed)) and perceived control over air velocity (Spearman's rho = -0.204; p= 0.006 (1-tailed)). Those that use their windows relatively infrequent feel less in control over ventilation, air velocity and temperature in winter.

The frequency of clothing adjustment was *not* significantly correlated with perceived control over temperature in winter, ventilation or air velocity.

[INSERT TABLE 8 ABOUT HERE]

[INSERT FIGURE 10 ABOUT HERE]

Correlation between measured and perceived thermostat speed

For each building available control over temperature in winter was objectified by measuring the thermostat speed (Table 6 and 7). At the same time information was obtained on perceived control over temperature by asking respondents how fast their thermostats normally respond (with answering categories 1. slow, 2. not slow / not fast, 3. fast).
For each building the average *perceived* thermostat speed score was derived to allow comparison with the average *measured* thermostat speed in each building during the interventions. See Figure 11. The data points are numbered and refer to the different buildings, i.e. label '1' indicates building X1. The intervention results refer to average outcomes of the upward intervention as summarized in Table 6 (final column). No scores are presented for building X2 and X6 because these buildings did not have adjustable thermostats (X6) or offered only very limited possibilities for temperature adjustment indirectly through the Building Management System (X2).

A positive, strong correlation between measured (average) thermostat speed and perceived thermostat speed was found (Pearson's test R = 0.834, R^2 = 0.695; p = 0.010 (1-tailed)). This indicates that subjective thermostat speed as perceived by occupants (on a 3-point scale) is a good indicator for objective, measured thermostat speed.

[INSERT FIGURE 11 ABOUT HERE]

General discussion

This field study investigated a selection of nine modern Dutch office buildings, spread out over the Netherlands. Due to practical reasons we used a restricted sample. So formally spoken, the buildings are not a true representative sample of Dutch office buildings and therefore this study should be regarded as a first pilot study that presents an indication of the personal control status-quo in the average modern office building in the Netherlands.

As far as the thermostat effectiveness measurements are concerned: the outcomes should be regarded with some prudence. Due to practical circumstances it was not possible to quantify the thermostat speed in all buildings under comparable weather conditions. All experiments were done during the winter months, however: outside temperatures differed. For comparison: the maximum outside air temperatures (at around 2 PM) during the experiments were: building X1: +17 °C (63 °F); building X2: +9 °C (48 °F); building X3: +10 °C (50 °F); building X4: +5 °C (41 °F); building X5: +6 °C (43 °F); building X6: -3 °C (27 °F); building X7: +10 °C (50 °F); building X8: +5 °C (41 °F) and building X9: 12 °C (54 °F). Ideally the thermostat effectiveness measurements should be repeated (in a future study) in each building one or two times with other outside temperatures to further validate the thermostat speed results under winter conditions as presented in this paper. Having said that: the objective of the measurements was to obtain a general idea of typical response times and step responses when using adjustable thermostats in Dutch office buildings under winter conditions applying a standard assessment approach. That objective was met.

Comparison of the results of this study to other field studies is not straightforward, partly because this type of study is quite rare. The authors are not aware of any other field studies that used thermostat effectiveness measurements similar to the ones described in this paper.

As far as the link between exercised and perceived control is concerned: our results show that those that use their adjustable thermostats less frequent than monthly score significantly lower on perceived control over temperature in winter than those that use their thermostats daily, weekly or monthly. This finding is partly in contradiction with the results of Paciuk (1990). She conducted a somewhat comparable field study in office buildings in Israel and found a reversed U-shape correlation between exercised control and perceived control. Israeli office workers that very often were involved in indoor climate related control actions (once a day or even more frequent) *and* those that hardly ever (monthly or less than monthly) were involved in such control actions were significantly more dissatisfied with their thermal environment than those that only now and then (about on a weekly basis) used thermostats, changed clothing etc. The difference with the results from our study and those from Paciuk might be explained by the fact that Paciuk’s study was conducted in Israelian buildings in a very different (much warmer) outdoor climate with buildings mostly in cooling mode instead of heating mode.

Another interesting study to compare our results with is the Finnish field study done by Karjalainen & Koistinen (2007). They interviewed a total of 27 office workers in their office space, distributed over 13 different buildings. Similar to our findings, they found that temperature controls are often not used when people experience thermal discomfort. The Finnish researchers identified several problems with adjustable thermostats that might explain why there are not used as frequent (and effective) as expected: (-) it is often not known that there is the possibility for individual temperature control in a room, (-) lights and symbols on user interfaces are often not understood correctly, and (-) it is not always known (visible) whether temperature controls are operating or not. The overall conclusion of Karjalainen & Koistinen was that adjustable thermostats often are overcomplicated and not well designed and constructed without a realistic view of office building occupants.

Haldi and Robinson (2007) studied personal control over indoor climate in eight Swiss office buildings under summer conditions. Obviously it is not easy to compare their summer results with the winter results presented here. Nevertheless, Haldi and Robinson (2007) also found that people normally react to suboptimal temperatures not just by adjusting thermostats but by a complex array of control actions (changing activity level, opening or closing windows, taking warm or cold drinks, etc.).

The field study presented here identified several correlations but cannot answer yet in detail what the underlying mechanisms are that dictate how available, exercised and perceived control interact and how they affect other aspects. Some further questions that need to be answered in the future are:

- Does frequency of control use impact perceived control or is it the other way around?
- How does effectiveness of control actions relate to the perception of being (or not being) in control over one's indoor climate?
- How are (periodic) clothing adjustments related to the presence or absence of other control options?
- Are the relations any different if control over indoor climate is offered at workstation level (through so-called personal or microclimatisation systems) and not at room level (with room based HVAC systems)?
- How is (available, exercised and perceived) control related to health and comfort of building occupants?
- How is (available, exercised and perceived) control related to performance and productivity of building occupants?

One of the clear findings of the field study was that about 80% of the office workers do not take energy effects into account when using indoor climate controls. Some might see this as an invitation to impose (extra) restrictions on the use of controls in offices (or even worse: to skip them altogether). But we also found that 'bans' on the use of adjustable thermostats and operable windows will make people feel less in control over their indoor climate which on it's turn increases the risk for health and comfort problems (Boerstra, Beuker, Loomans & Hensen, 2013). A better solution might be to develop indoor climate control systems and control algorithms that allow office workers some (fast enough) control over their indoor climate while at the same time discourage extreme energy inefficient use of thermostats and operable windows.

Conclusions

The first objective of the field study was to investigate what kind of control Dutch office workers have over temperature in winter (available control), to map how often their winter controls are used (exercised control) and to identify how much control the office workers perceive to have over temperature in winter (perceived control).
The field study in nine office buildings showed that the average office worker in these buildings does have access to both an adjustable thermostat and an operable window for indoor climate control in winter. As far as exercised control is concerned, the occupants in the buildings use adjustable thermostats in winter less frequent than operable windows. Also winter adaptation by clothing adjustment is more popular than thermostat use. The majority of occupants do not react to too low temperatures in winter by adjusting thermostats. Instead they resort to actions like adding extra clothing, raising metabolism, taking a hot drink or internal coping (just accepting the situation). Four out of five occupants do not take energy use effects into account when using adjustable thermostats and other controls.
Only 31% indicated to be satisfied with the amount of control they have over their indoor climate. Perceived control over temperature in winter was around 3 on a 7-point scale (1= no control whatsoever, 7 = full control). Which was considerable lower than for example perceived control over sun penetration or perceived control over light.
The number of colleagues one shares the workplace with has a considerable effect on perceived control over temperature (and ventilation): more officemates means a lower level of perceived control over one’s indoor climate. Also men and those that have workstations farther away from the facade have a significantly lower level of perceived control over indoor climate in winter.

The second objective was to objectify the amount of control over temperature in winter through thermostat effectiveness measurements. An assessment method has been developed to quantify the amount of control over temperature that was available to the occupants in heating mode.
From the application of the method in the investigated buildings it is concluded that the assessment procedure is useful and that buildings show a large variation in thermostat effectiveness (for example, thermostat speed differed between buildings from +0.2 to +2.5 K/hr for upward interventions). Upward adjustments of thermostats were found to be more effective than downward adjustments.

The third objective of the study was to investigate how available control (access to adjustable thermostats and operable windows, but also measured effectiveness of thermostats) and exercised control (frequency of use of controls in winter) impact the level of control over indoor climate in winter as experienced by office workers (perceived control).
A clear link between available control and perceived control was found. Those occupants that reported having access to adjustable thermostats scored significantly better (higher) on the 7-point perceived control scale than those that did not. The same is true for access to operable windows.
Frequency of use of controls was linked to perceived control over indoor climate. Those that use their adjustable thermostats less frequent than monthly or never score significant lower on perceived control over temperature in winter than those that use them monthly or more often. Also, a strong correlation has been found between measured thermostat speed in heating mode and average thermostat speed as perceived by the occupants during winter.

Future field research in other buildings (preferably with the involvement of environmental psychologists) should be performed before the conclusions from this study can be generalized.

Acknowledgements
The authors would like to thank Patrick Creemers and Richard Claessen for their assistance during the field study and their help with the analysis of the data. At the time of the field study Patrick and Richard were Master students of the unit Building Physics & Services of the Eindhoven University of Technology in the Netherlands.

References

Baarda, D.B., De Goede M.P.M. and Van Dijkum, C.J., 2011. *Basisboek Statistiek met SPSS*. Groningen, the Netherlands: Noordhoff Publishers.

Baarda, D.B. and De Goede M.P.M., 2006. *Basisboek Methoden en Technieken*. Groningen, the Netherlands: Noordhoff Publishers.

Bell, P.A., Greene, T.C., Fisher, J.D. and Baum, A., 2005. *Environmental Psychology*. Forth Worth, TX, USA: Hartcourt Brace College Publishers.

Boerstra A.C. and Beuker T.C. 2011. Impact of perceived personal control over indoor climate on health and comfort in Dutch offices. In: *Indoor Air 2011:* Proceedings of the 12th International Conference on Indoor Air and Climate.

Boerstra, A., Beuker T., Loomans M. & Hensen J., 2013. Impact of available and perceived control on comfort and health in European offices. *Architectural Science Review* 56(1): 30-41.

Bordass, B., Leaman, A., Ruyssevelt, P. 2001. Assessing building performance in use 5: conclusions and implications. *Building Research and Information* 2001; 29(2).

Brager, G.S. and R.J. de Dear, 1998. Thermal adaptation in the built environment: A literature review. *Energy and Buildings* 27(1): 83-96.

Brager, G.S., Paliaga, G., DeDear, R., 2004. Operable windows, personal control and occupant comfort. *ASHRAE Transactions* Vol. 110, Part 2.

Haldi, F. and Robinson, D., 2008. On the behavior and adaptation of office occupants. *Building and Environment* , 43 (12) , pp. 2163-2177.

Karjalainen, S. and Koistinen, O., 2007. User problems with individual temperature control in offices. *Building and Environment* 2007; 42(8).

Nicol, J.F. and Humphreys, M.A. (1973) Thermal comfort as part of a self-regulating system. *Building Research and Practice (J. CIB)* 6(3), pp. 191-197.

Paciuk. 1990. The role of personal control of the environment in thermal comfort and satisfaction at the workplace. In: *Proceedings ECRA Conference 1990*, Environmental Design Research Association.

Rohles, F.H., 2007. Temperature & Temperament: A Psychologist look at comfort. *ASHRAE Journal*, February 2007: pp. 14-22.

Veitch, J.A. and Newsham, G.R., 2000. Exercised control, lighting choices and energy use: an office simulation experiment. *Journal of Environmental Psychology* 2000, 20, pp. 219-237.

TABLES

Table 1. Characteristics of the nine office buildings investigated.

Aspect	Building								
	X1	**X2**	**X3**	**X4**	**X5**	**X6**	**X7**	**X8**	**X9**
Type of organization	Housing corporation	Main office HVAC product manufacturer	Departmental building government	Town hall	Main office construction company	Main office façade building product manufacturer	Head quarters consumer organization (building I)	Head quarters consumer organization (building II)	Tax office government
Year of construction / latest major renovation	1948 / 2000	2006 / -	1967 / 1998	2003 / -	1986	2010 / -	1971 / 1990	1958 / 2005	2011 / -
Floor surface	5,000 m^2 (54,000 ft^2)	7,300 m^2 (79,000 ft^2)	33,000 m^2 (355,000 ft^2)	6,400 m^2 (69,000 ft^2)	4,100 m^2 (44,000 ft^2)	2,000 m^2(22,000 ft^2)	11,600 m^2 (125,000 ft^2)	11,200 m^2 (121,000 ft^2)	46,600 m^2 (502,000 ft^2)
Office layout	mainly enclosed spaces, some office landscape	mainly office landscape	enclosed spaces (mainly 1, 2 and 4 person offices)	enclosed spaces (mainly 1, 2, 4 and 6 person offices)	mostly 1 person rooms	mainly office landscape	partly enclosed spaces, partly office landscape	mainly office landscape	partly enclosed spaces, partly office landscape
Number of floors	3	3	21	5	4	3	8	8	25
Average floor depth	25 m (82 ft)	15 m (49 ft)	23 m (75 ft)	15 m (49 ft)	13 m (42 ft)	16 m (52 ft)	15 m (49 ft)	15 m (49 ft)	23 m (75 ft)
Number of workstations	150	520	1400	220	65	35	680	450	2600
Percentage of glazing	±20%	±70%	±40%	±50 & 80%	±20%	±90%	±50%	±60%	±70%
U-value glass	1.1 m^2K/W	0.7 m^2K/W	ca. 2 m^2K/W	1.6 m^2K/W	ca. 3 m^2K/W	1.1 m^2K/W.	ca. 3.5 m^2K/W	1.2 W/m^2K	1.1 W/m^2K.
Ventilation system	mechanical supply and exhaust system with central heat recovery (twin coil)	mechanical supply and exhaust (CAV) with heat recovery via enthalpy wheel	mechanical supply and exhaust with central recirculation	mechanical supply and exhaust (CAV), steam humidification and central heat recovery via Resolair units	mechanical air supply and exhaust with heat recovery via enthalpy wheel	air supply via double, folding façade and operable windows, mechanical exhaust in kitchen, toilet etc	natural supply via large and small operable windows, no mechanical exhaust	mechanical supply and exhaust , humidification of the ventilation air and heat recovery via twin coil	mechanical supply and exhaust system (VAV) with under floor supply
Heating system	after heater in above ceiling VAV induction-unit connected to district heating system	heating via 4 pipe climate ceiling connected to geothermal heating / cooling storage system and heat pump	after heater in DID induction unit connected to district heating system	radiators and convectors connected to district heating system	radiators connected to natural gas heaters	slab heating connected to geothermal installation with heat pump	radiators connected to natural gas heaters	radiators and ventilator convectors connected to natural gas heaters and central preheating of the ventilation air	slab heating with additional convectors connected to central heat and cold storage in the soil with heat pump and central preheating of the supply air
Cooling system	local cooling via VAV induction-units	local cooling via climate ceiling (see above) and central precooling of ventilation air	after cooler in DID induction unit	central precooling of the supply air	some central precooling of the supply air	slab cooling (see above)	none	ventilator convectors connected to cooling machines and central precooling of the supply air	slab cooling (see above) and central precooling of the supply air
Temperature control winter	wall thermostat	indirect via desktop computer	wall thermostat with on-off	adjustable thermosta	adjustable thermosta	none	adjustable non-thermostatic	adjustable thermostatic valves on	adjustable thermostatic valves on

		connected to building management system	presence knob	tic valves on radiators and convectors	tic valves on radiators		valves on radiators	radiators and ventilator convectors	convectors; sometimes also wall thermostats
Temperature control summer	wall thermostat	indirect via desktop computer connected to building management system	wall thermostat with on-off presence knob	none	none	none	none	adjustable thermostatic valves on ventilator convectors	None
Ventilation control	operable windows (medium size)	operable windows (medium size)	operable window (medium)	partially operable windows (medium)	operable windows (medium, zigzag double sliding)	operable windows (large, in double folding façade)	operable windows (small and large combined)	operable windows (large)	operable windows (medium)

Table 2. Exercised control in winter: frequency of use for temperature knobs (adjustable thermostats), operable windows and clothing adjustments. Note that the total amount of respondents for this part (interview part) was 161; in the case of operable window use and clothing adjustment a few respondents (respectively 2 and 16) did not answer the question.

Use of controls - WINTER

		Count	Perc.
Operable window use	daily	30	19%
	weekly	38	24%
	monthly	23	14%
	less than monthly / never	48	30%
	not applicable	20	13%
	Total	159	100%
Temperature knob use	daily	16	10%
	weekly	18	11%
	monthly	31	19%
	less than monthly / never	48	30%
	not applicable	48	30%
	Total	161	100%
Clothing adjustment	daily	33	23%
	weekly	38	26%
	monthly	26	18%
	less than monthly / never	48	33%
	Total	145	100%

Table 3. Incidence of standard reactions when feeling cold, in order of frequency (n=116). People were free to indicate up to three reactions; this explains why the numbers add up to more than 100%.

Standard reaction	**Percentage of respondents that normally resort to this reaction**
Add extra clothing	66%
Adjust thermostat (upward)	43%
Internal coping (just accepting)	15%
Raise metabolism	11%
Drink warm drink	11%
Contact building manager	3%
Other	24%

Table 4. Perceived control over temperature in winter, ventilation and air velocity on a 7 point scale (1 = no control whatsoever and 7 = full control); perceived control over temperature in summer, sun penetration, light and sound is added for comparison purposes.

	N		Mean	Standard Deviation	Median	Mode
	Valid	Missing				
control over temperature in winter	233	3	3.24	1.76	3	2
control over ventilation	233	3	3.03	1.91	3	1
control over air velocity	229	7	2.14	1.56	1	1
control over temperature in summer	231	5	2.91	1.57	3	2
control over sun penetration	235	1	4.33	2.07	5	5
control over light	235	1	4.34	2.12	5	7
control over sound	235	1	3.11	1.77	3	1

Table 5. Correlation between perceived control over indoor climate (on a scale from 1 = no control whatsoever and 7 = full control) and sex, number of officemates and distance of workstation to facade; * means significant (1-tailed) at the 0.05 level, ** means significant (1-tailed) at the 0.01 level.

		Sex (female, male)	**Number of officemates (none, 1 or 2, 3 until 9, 10 or more)**	**Distance of workstation to facade (<2.5 m (8 ft), 2,5-5m (8-16 ft), >5m (16 ft))**
Perceived control over temperature in winter (scale 1-7)	Spearman's rho	**-0.111***	**-0.375****	**-0.243****
	Significance (1-tailed)	**0.045**	**0.000**	**0.000**
	N	233	229	230
Perceived control over temperature in summer (scale 1-7)	Spearman's rho	-0.080	-0.064	**-0.132***
	Significance (1-tailed)	0.112	0.170	**0.023**
	N	231	227	228
Perceived control over ventilation (scale 1-7)	Spearman's rho	0.022	**-0.139***	**-0.264****
	Significance (1-tailed)	0.369	**0.017**	**0.000**
	N	233	229	230
Perceived control over airspeed (scale 1-7)	Spearman's rho	0.065	0.068	-0.086
	Significance (1-tailed)	0.164	0.154	0.098
	N	229	226	226
Perceived control over sun penetration (scale 1-7)	Spearman's rho	-0.043	**-0.187****	**-0.206****
	Significance (1-tailed)	0.257	**0.002**	**0.001**
	N	235	231	232
Perceived control over light (scale 1-7)	Spearman's rho	0.010	**-0.328****	**-0.254****
	Significance (1-tailed)	0.441	**0.000**	**0.000**
	N	235	231	232
Perceived control over sound (scale 1-7)	Spearman's rho	0.027	**-0.389****	**-0.244****
	Significance (1-tailed)	0.339	**0.000**	**0.000**
	N	235	231	232

Table 6. Results for the UPWARD experiments (thermostat adjusted from low to high setting); 1 Kelvin/hr = 1.8 Fahrenheit/hr.

IN THIS TABLE THERE IS A STRANGE HALF-LINE JUMP IN LINES NOW BETWEEN X1 AND X2. PLEASE REPAIR.

	Number of experiments	STEP RESPONSE (Kelvin)			RESPONSE TIME (minutes)			HALFTIME (minutes)			THERMOSTAT SPEED*	
		Min.	**Avg.**	Max.	Min.	**Avg.**	Max.	Min.	**Avg.**	Max.	(Kelvin/ min)	(Kelvin/ hr.)
X1	3	-0.4	**+0.5**	+1.6	90	**135**	175	5	**50**	100	+0.005	**+0.3**
X2**	3	+0.1	**+0.9**	+1.4	30	**50**	90	15	**25**	∞	+0.018	**+1.1**
X3	4	-0.2	**+0.7**	+1.2	130	**195**	290	65	**110**	∞	+0.003	**+0.2**
X4	7	+1.4	**+4.2**	+5.9	155	**190**	255	30	**50**	85	+0.042	**+2.5**
X5	5	+1.5	**+3.7**	+6.5	160	**190**	240	40	**60**	70	+0.031	**+1.9**
X6***	-	-	-	-	-	-	-	-	-	-	-	-
X7	3	+1.8	**+2.7**	+4.2	130	**160**	195	40	**40**	45	+0.034	**+2.0**
X8	4	+0.4	**+0.7**	+0.9	28	**155**	205	7	**65**	90	+0.005	**+0.3**
X9	4	+1.0	**+1.1**	+1.1	120	**135**	160	25	**40**	55	+0.014	**+0.8**
Average all buildings			**+1.8**			**151**			**55**			+1.1

** Thermostat speed relates to the effectiveness of temperature controls and expresses how fast air temperature changes during the first period (until halftime); thermostat speed is calculated by dividing 1/2 of the step response with the halftime value and then transforming this from Kelvin per minute to Kelvin per hour.*

*** Building X2 did not have adjustable wall thermostats or radiator/convector thermostatic valves; instead people could change the temperature of their own workspace (setpoint of the local climate ceiling) via their desktop computer that was connected with the building management system.*

**** Building X6 turned out not to have possibilities for temperature control at workplace level; therefore no measurement outcomes are presented for this building.*

Table 7. Results for the DOWNWARD experiments (thermostat adjusted from high to low setting); 1 Kelvin/hr = 1.8 Fahrenheit/hr.

	Number of experiments	STEP RESPONSE (Kelvin)			RESPONSE TIME (minutes)			HALFTIME (minutes)			THERMOSTAT SPEED*	
		Min.	**Avg.**	Max.	Min.	**Avg.**	Max.	Min.	**Avg.**	Max.	(Kelvin/min)	(Kelvin/hr)
X1	4	-1.8	**-0.1**	+0.9	55	**135**	220	15	**45**	∞	-0.001	**-0.1**
X2**	6	-1.2	**-0.5**	-0.1	40	**100**	185	15	**70**	∞	-0.004	**-0.2**
X3	6	-0.7	**+0.5**	+1.5	25	**130**	240	5	**25**	∞	+0.010	**+0.6**
X4	2	-2.4	**-1.3**	-0.2	255	**260**	260	105	**180**	250	-0.004	**-0.2**
X5	5	-1.5	**-0.8**	+0.9	220	**245**	265	55	**95**	170	-0.004	**-0.3**
X6***												
X7	2	-0.3	**+0.5**	+1.2	175	**190**	200	15	**100**	190	+0.003	**+0.2**
X8	5	-1.9	**-1.0**	-0.3	24	**55**	110	6	**35**	90	-0.014	**-0.9**
X9	5	-0.6	**+0.5**	+1.0	50	**95**	140	15	**20**	40	+0.013	**+0.8**
Average all buildings			**-0.3**			**151**			**71**			**+0.0**

** Thermostat speed relates to the effectiveness of temperature controls and expresses how fast air temperature changes during the first period (until halftime); thermostat speed is calculated by dividing 1/2 of the step response with the halftime value and then transforming this from Kelvin per minute to Kelvin per hour.*

*** Building X2 did not have adjustable wall thermostats or radiator/convector thermostatic valves; instead people could change the temperature of their own workspace (set point of the local climate ceiling) via their desktop computer that was connected with the building management system.*

**** Building X6 turned out not to have possibilities for temperature control at workplace level; therefore no measurement outcomes are presented for this building.*

Table 8. Correlation between exercised control and perceived control; * means significant (1-tailed) at the 0.05 level, ** means significant (1-tailed) at the 0.01 level.

		Perceived control (1= no control whatsoever - 7= full control)		
		Control over temperature in winter	Control over ventilation	Control over air velocity
Frequency of adjustable thermostat use in winter (daily, weekly, monthly, never)	Spearman's rho	**-0. 456****	-0.124	-0. 023
	Significance (1-tailed)	0.000	0.059	0.388
	N	161	161	157
Frequency of operable window use in winter (daily, weekly, monthly, never)	Spearman's rho	**-0.197****	**-0.380****	**-0.204****
	Significance (1-tailed)	0.007	0.000	0.006
	N	159	159	155
Frequency of clothing adjustment (daily, weekly, monthly, never)	Spearman's rho	-0.095	-0.030	0.053
	Significance (1-tailed)	0.129	0.361	0.267
	N	145	145	141

FIGURES

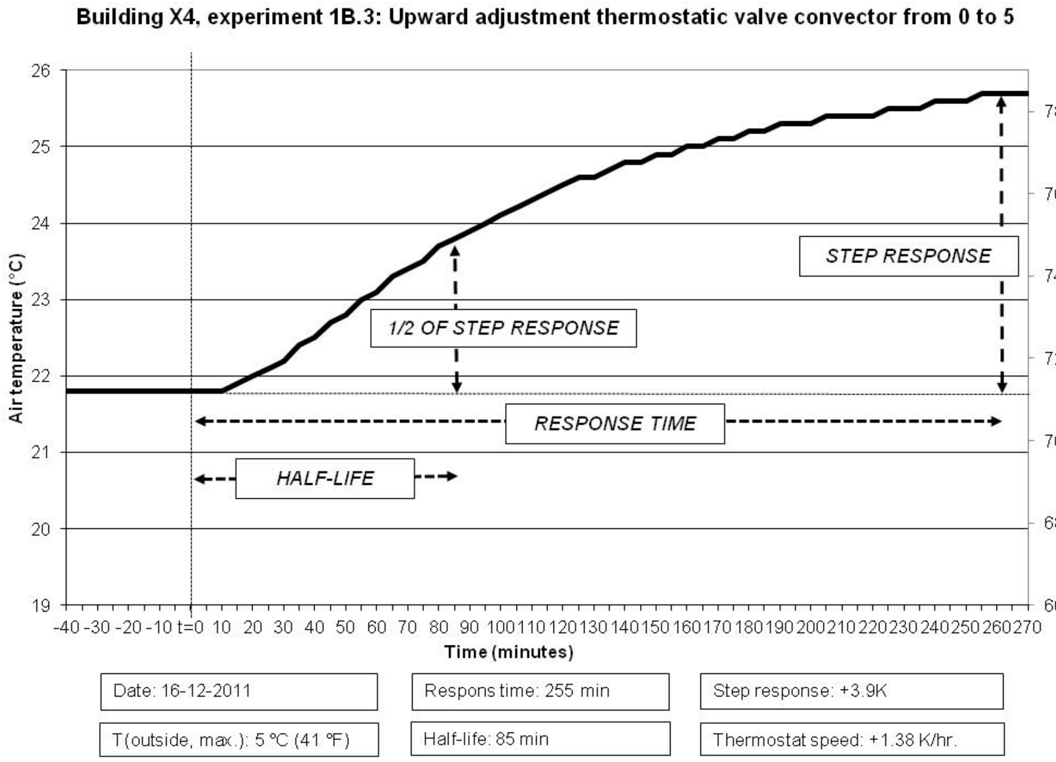

Figure 1. Example nr. 1 of an upward thermostat effectiveness measurement outcome and explanation of the concepts response time, step response and half-life. Note that below the figure additional information is presented such as the date of the experiment and the maximum outside temperature of that day according to the KNMI (Dutch Meteorological institute).

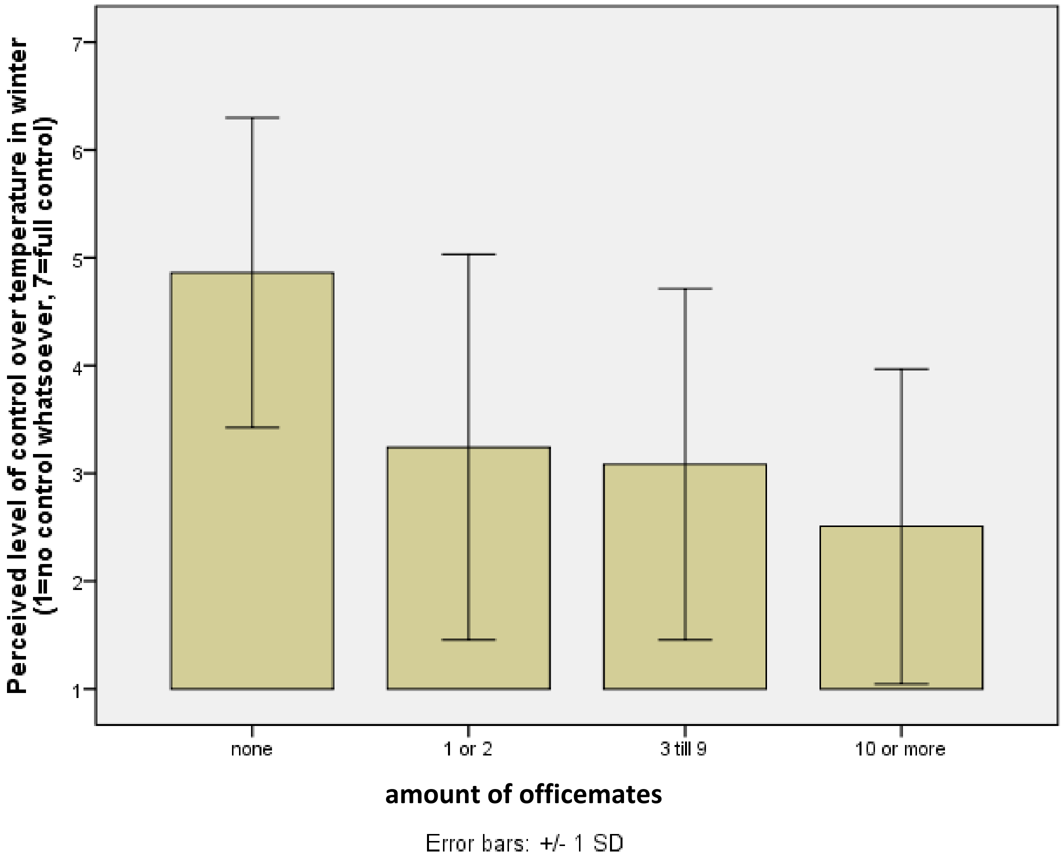

Figure 2. Impact of the number of colleagues (officemates) the workspace is shared with on the perceived level of control over temperature in winter. Depicted are mean value and standard deviation of each group. The two variables are significantly correlated (spearman's rho -0.375; p=0.000 with 1-tailed test).

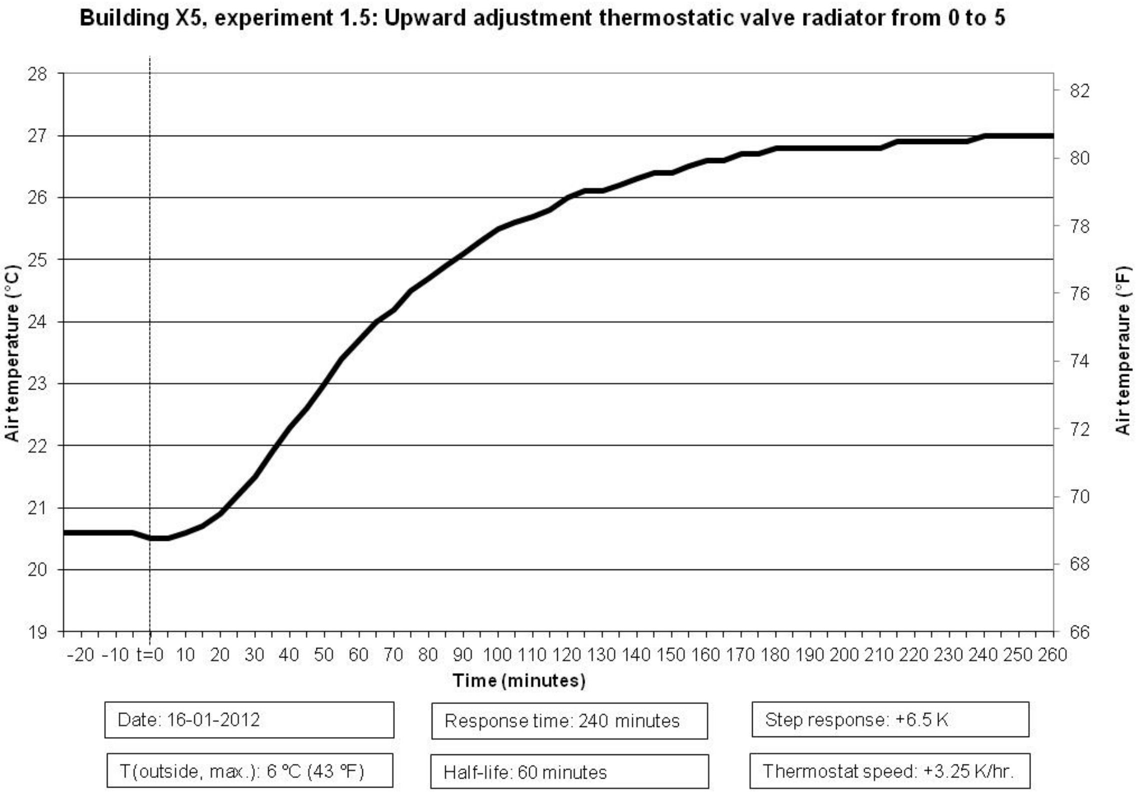

Figure 3. Example nr. 2 of an upward thermostat effectiveness measurement outcome.

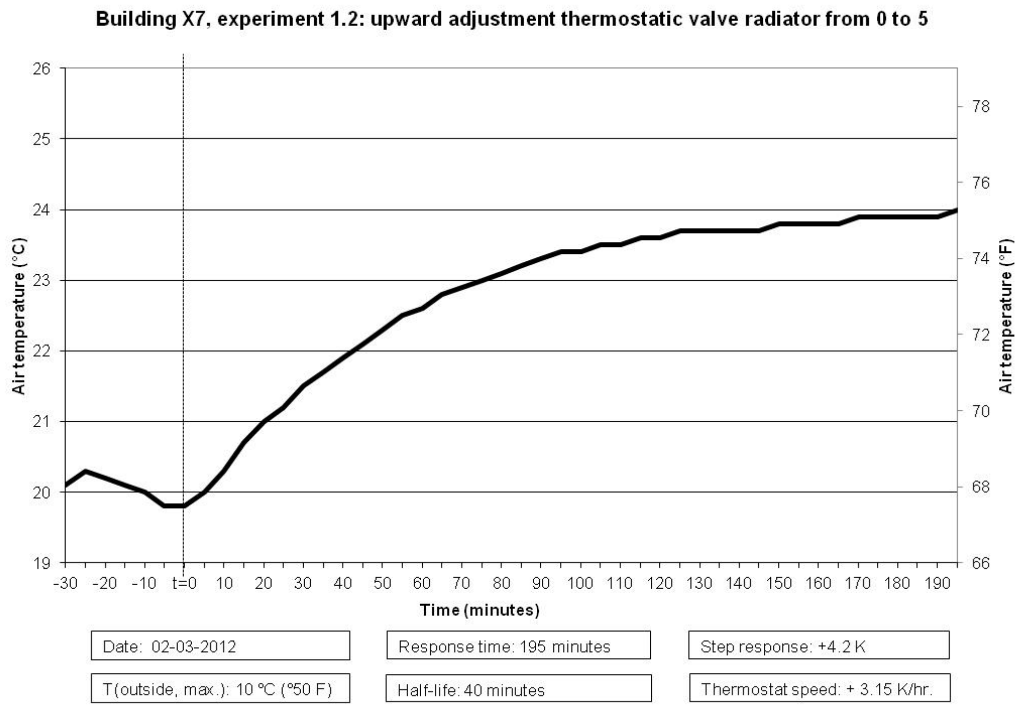

Figure 4. Example nr. 3 of an upward thermostat effectiveness measurement outcome.

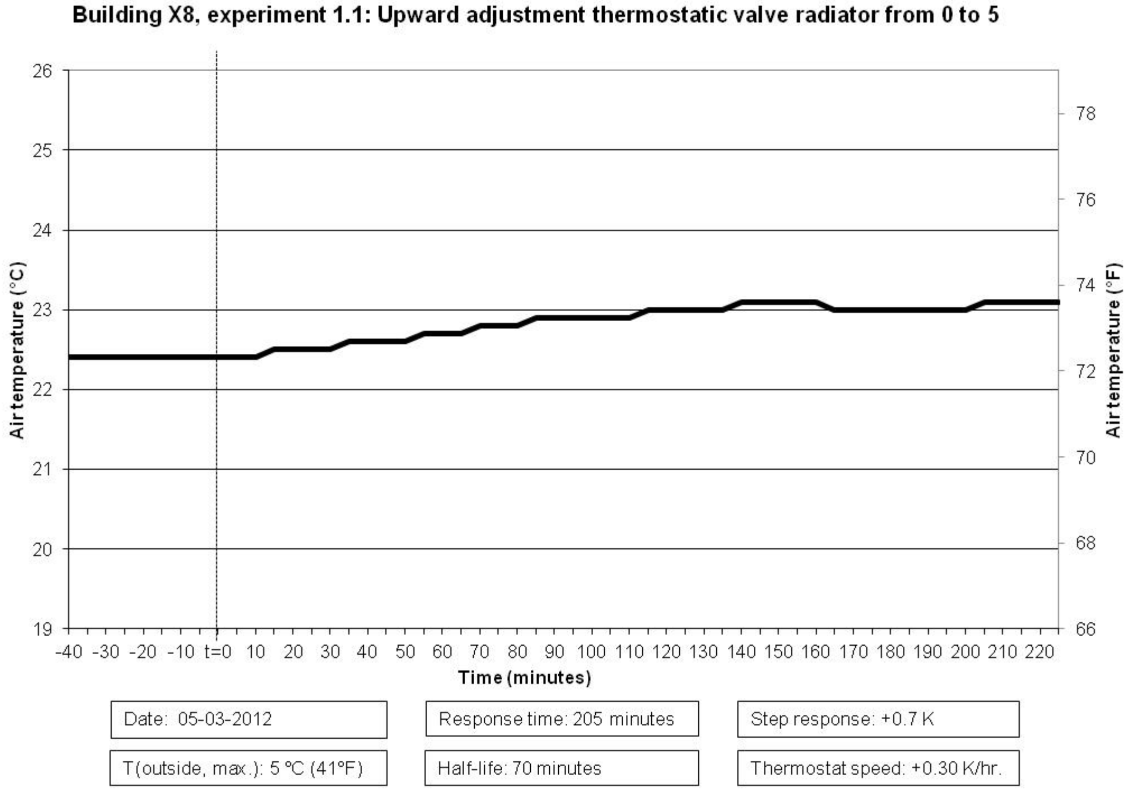

Figure 5. Example nr. 4 of an upward thermostat effectiveness measurement outcome; note that in this case adjustment of the thermostat apparently had little effect.

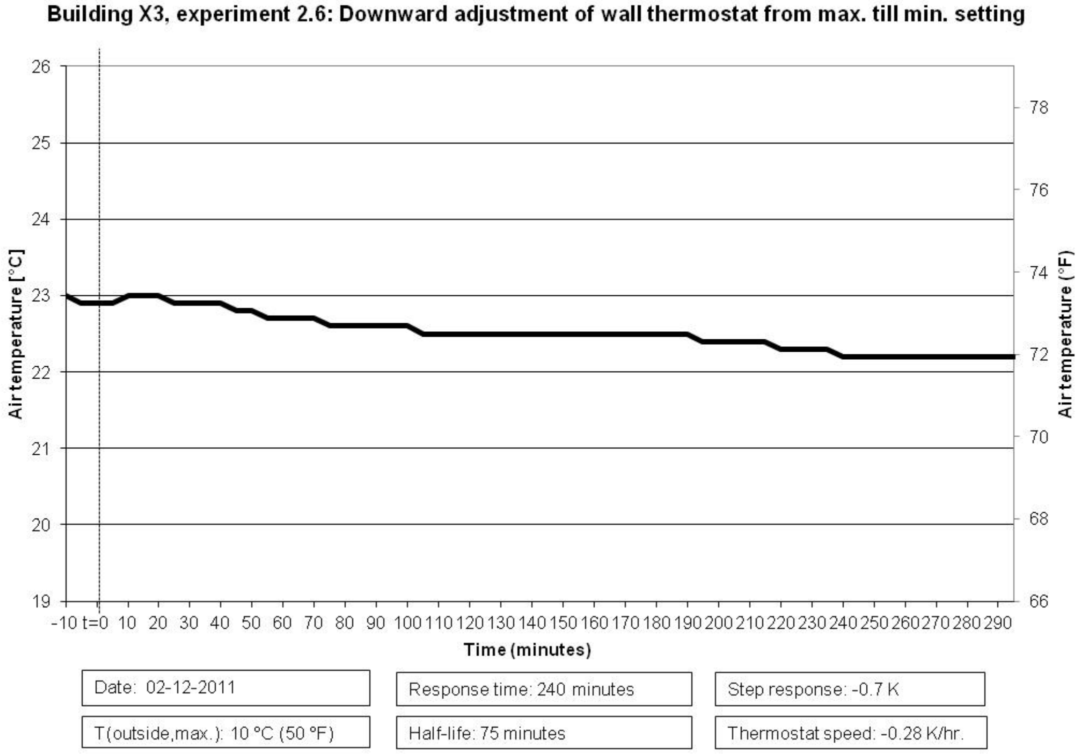

Figure 6. Example nr. 1 of a downward thermostat effectiveness measurement outcome; note that in this case adjustment of the thermostat apparently had little effect.

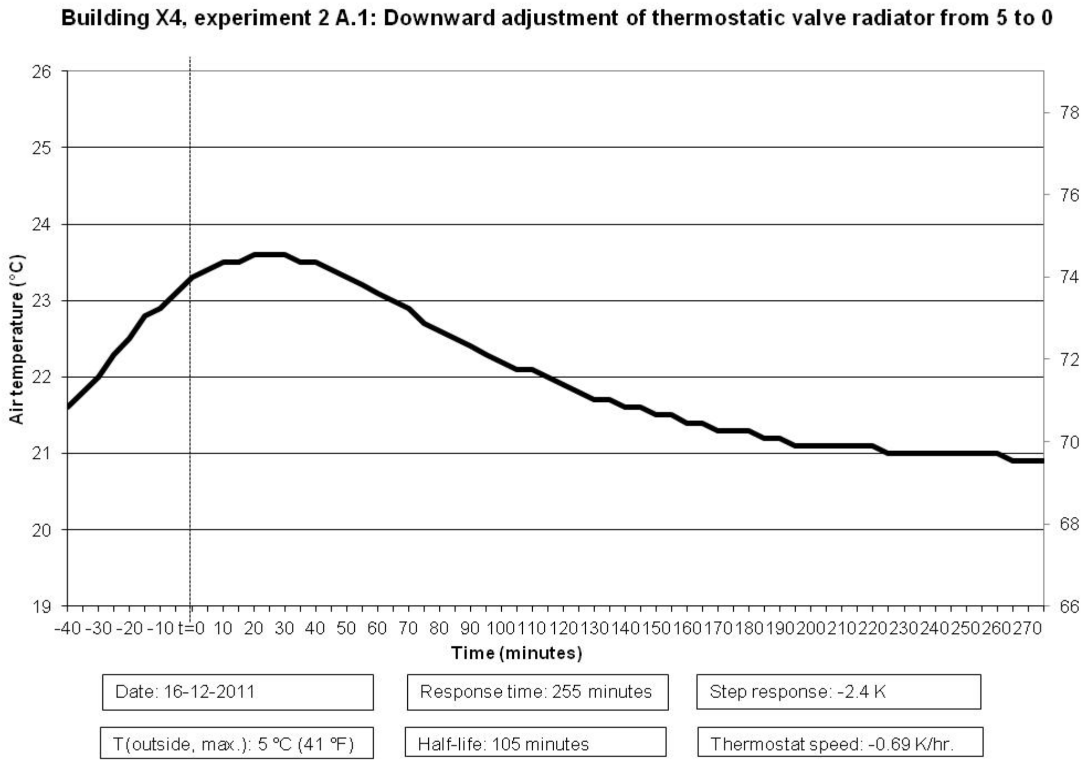

Figure 7. Example nr. 2 of a downward thermostat effectiveness measurement outcome.

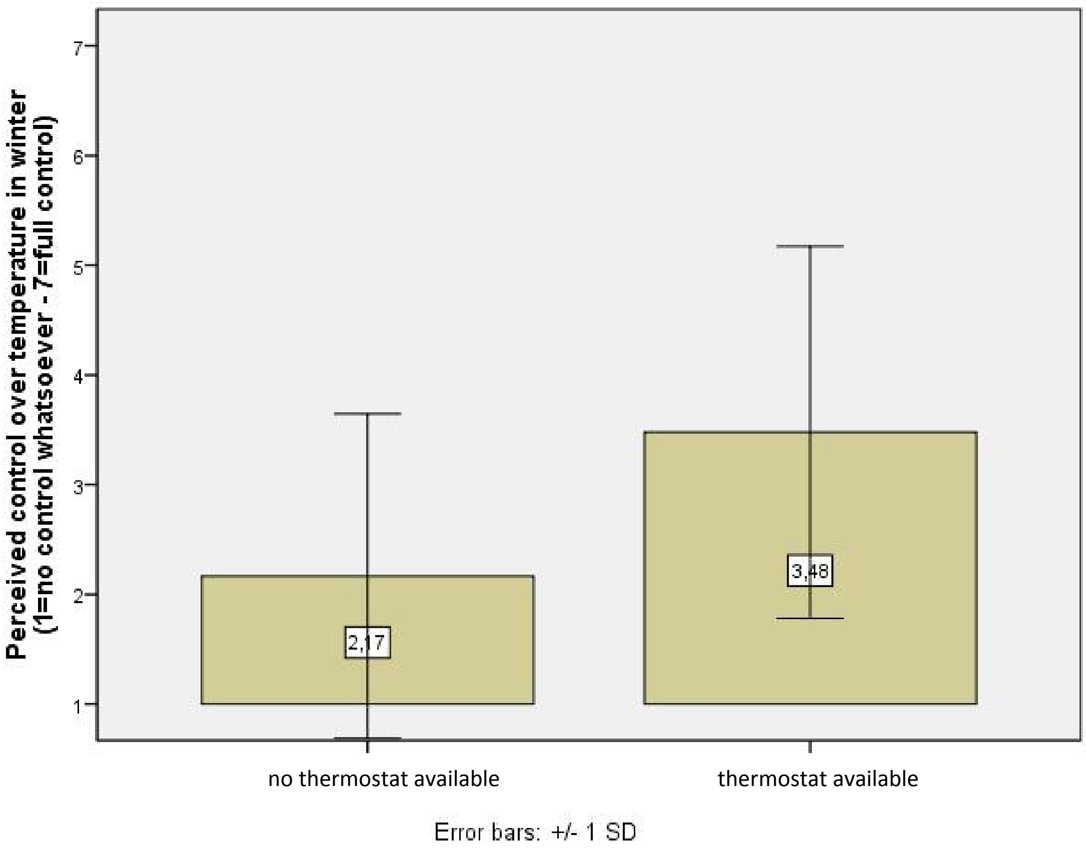

Figure 8. Impact of access to an adjustable thermostat (indicator for available control) on the perceived level of control over temperature in winter (n=161). Depicted are mean value and standard deviation of each group. The difference is statistically significant (Mann-Whitney U-test; mean rank respondents without thermostats is 55.29, mean rank for those with thermostats is 91.92; Z=-4.645; p = 0.000 (2-tailed)).

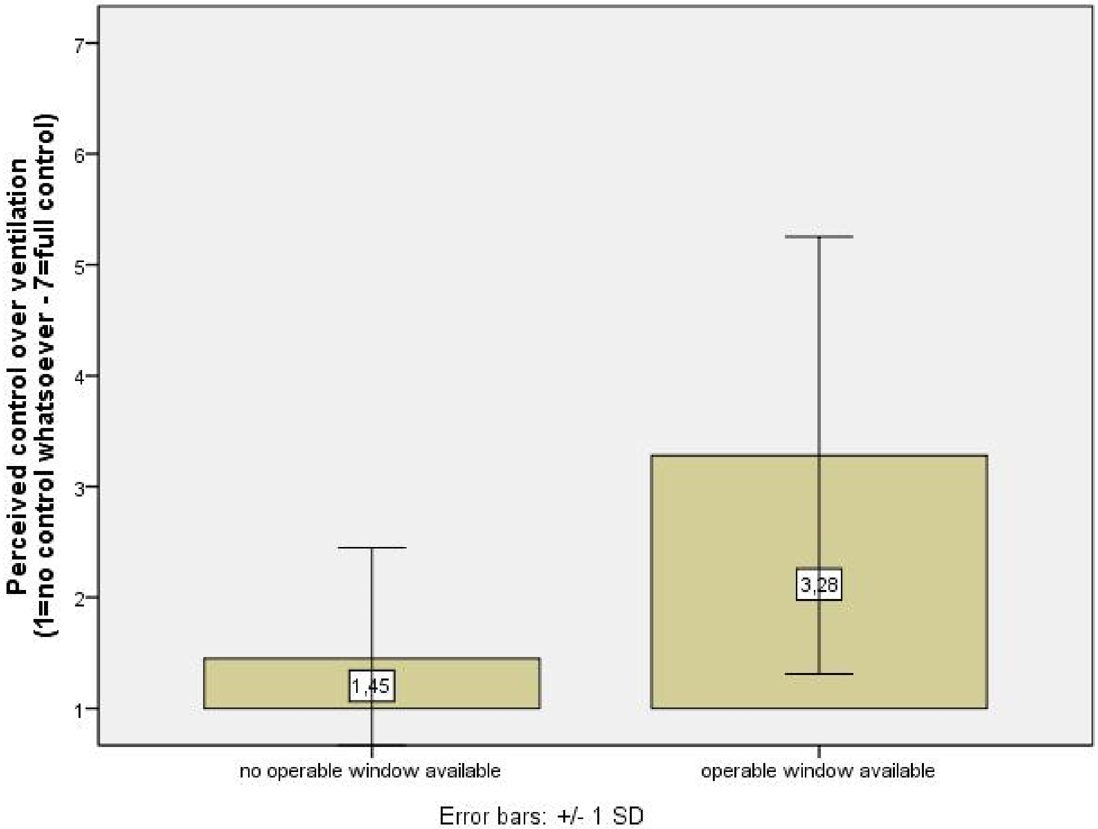

Figure 9. Impact of access to an operable window (indicator for available control) on the perceived level of control over ventilation (n=159). Depicted are mean value and standard deviation of each group. The difference is statistically significant (Mann-Whitney U-test; mean rank respondents without operable windows is 39.85, mean rank for those with operable windows is 85.78; Z= -4.269; p= 0.000 (2-tailed)).

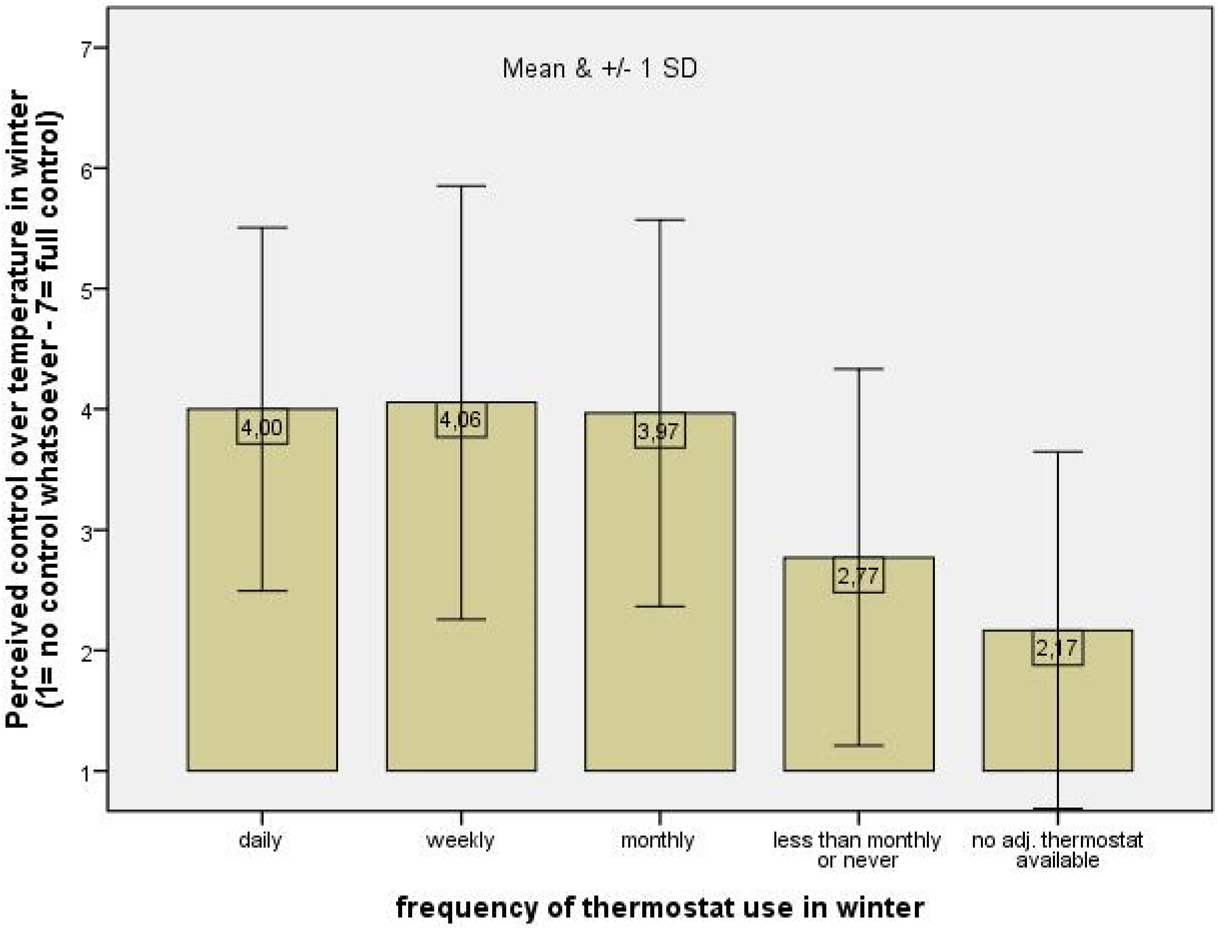

Figure 10. Frequency of adjustable thermostat use in winter (exercised control) and it's impact on perceived control over temperature in winter. The difference is statistically significant (Spearman's rho = -0.456; p= 0.000 (1-tailed)).

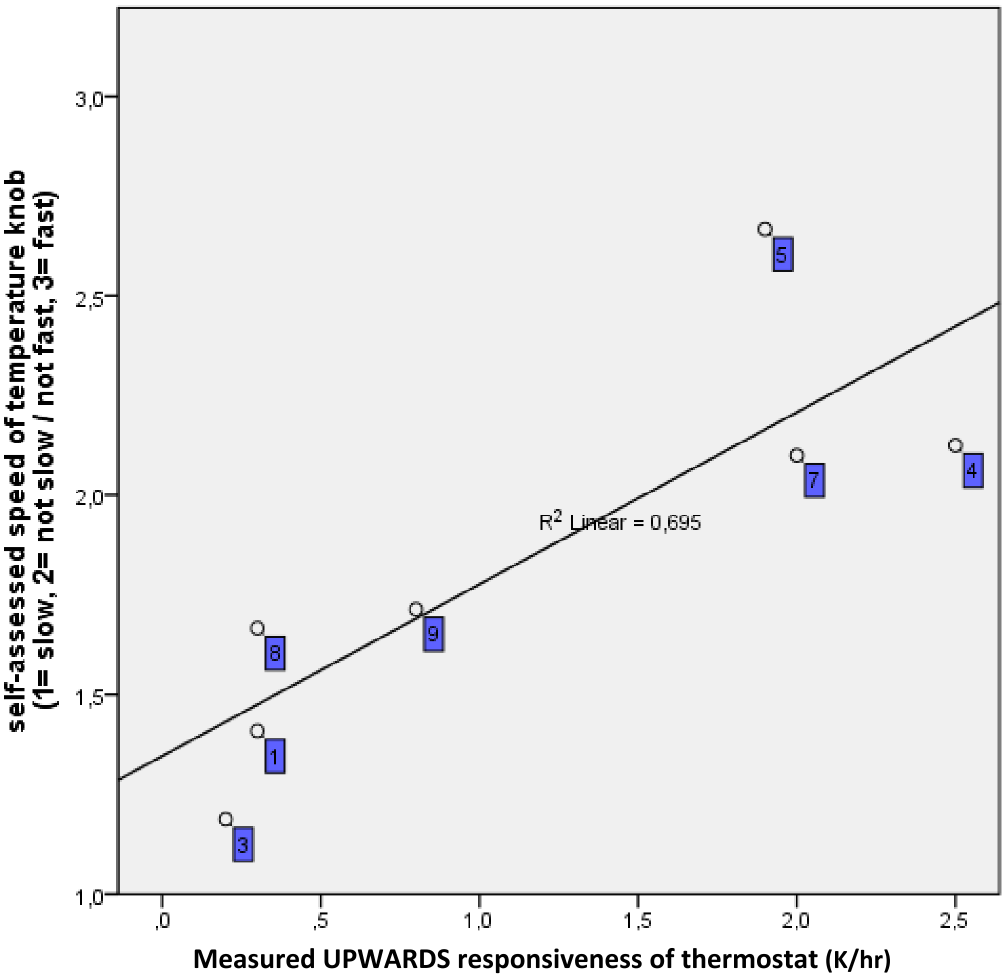

Figure 11. Correlation between objective average measured thermostat speed for each building and subjective average perceived thermostat speed; the correlation is statistically significant (Pearson's test R = 0.834, R^2 = 0.695; p = 0.010 1-tailed). Note that each data point refers to (the average of) *several* measurement / experiments done in one building (see table 6, 2nd column).