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Assessment of Occupant Adaptive Heating Behaviour in Office Buildings - A Pilot Field Study

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Abstract. Buildings are responsible for 39% of total global CO2 emissions worldwide, with 33% of energy consumption attributed to space heating in commercial buildings. Adaptive Heating Behaviour (AHB) of office users has a direct impact on energy use and depends on building characteristics which determine the heating load. This pilot field study focuses on the assessment of the AHB of office users of a recently retrofitted university building in Christchurch, New Zealand. AHB was reported by users during three consecutive days with a total heating degree days (HDD at 18°C) of 26.8. Indoor temperature and relative humidity were monitored during the study, and a qualitative analysis was performed to understand occupants’ behavioural patterns to maintain or recover thermal comfort in office settings. Participants were categorized according to (i) their reported thermal comfort issues at work, (ii) the adaptive responses they took to recover thermal comfort, and (iii) the effectiveness of such actions. The methods used in this pilot study to assess occupant AHB, were informative to future research on how to link environmental conditions to user behaviour in office settings, through the analysis of qualitative and quantitative data. Identifying patterns and triggers for AHB on a per-case basis is necessary, especially as AHB can significantly influence the building energy consumption.

1. Introduction
In non-domestic buildings, the user operation of Heating, Ventilation and Air Conditioning (HVAC) systems has an impact on building energy performance. The interaction between the occupants and the HVAC system depends not only on the conditions of the indoor and outdoor environments, but also on the intrinsic predispositions of the occupants [1,2]. Greater understanding of the behavioural aspects of energy use may provide reductions in operating costs, and enhanced comfort conditions and productivity for the building occupants [3]. The HVAC system is designed to offer stable conditions of thermal neutrality between the occupants and their surroundings; this is referred to as thermal comfort. The heating and/or cooling capacity of an HVAC system should be able to maintain an acceptable indoor thermal environment, which is dependent on weather conditions, building characteristics, and occupants’ individual factors (i.e. physiological and psycho-social predispositions). The parameters that dictate human thermal comfort have been studied in controlled laboratory settings as well as in field studies; they can also be estimated though mathematical modelling [4]. The requirements for general
thermal comfort and local thermal discomfort are specified in EN ISO 7730 standard [5], ASHRAE 55 [6], and EN15251 [7]. ASHRAE Standard 55-92 recommends operative temperature ranges of 24.5±1.5°C in summer and 22.0±2.0°C in winter for occupants performing light, sedentary activity in office spaces. The intensity of most of the thermal parameters included in the relevant standards has been directly linked to a predicted percentage of people finding the conditions unacceptable, and by determining psychophysical relationships between the parameters [8]. The adaptive model developed by de Dear and Brager [9] takes into consideration factors including psychological and contextual effects as influential to the human thermal comfort sensation.

Occupant adaptive behaviour for thermal comfort has been broadly studied, mostly for cooling services, as there is a significant impact by individual actions on building energy use [10]. Modifying the summer set point temperature and managing the dynamic variations of the indoor environment are often seen as the major opportunity for HVAC-related energy savings, based on the adaptive model [11]. Thermal adaptive behaviour is related to two types of action: (i) changing the conditions (affected by the building features and the opportunities for individual adaptation) to accord with comfort or (ii) changing the comfort temperature to yield prevailing conditions [12]. When an occupant faces a significant change in the indoor thermal environment, they choose whether or not to take an adaptive action, and this choice is influenced by environmental variables and other contextual factors [13]. Evaluation methods for thermal adaptive behaviour include both observational and self-reported surveys [14], but most of the applied methods are limited to investigating personal thermal adaptation and thermal adjustment of the indoor environment via windows, doors or blinds [10]. The evaluation of heating behaviour cannot be easily performed. For example, observations of the use of additional clothing or heaters may be more intrusive than surveying window openness.

This research employed surveys and measured room conditions to assess the use of space heating systems, the triggers that initiate the action taking, and the effectiveness of the adaptive actions taken by the occupants to recover thermal comfort. The term Adaptive Heating Behaviour (AHB) is used in this study to describe measures implemented by the occupants on cold days, including personal adaptation measures and the use of electric heaters.

2. Research Methodology
This section presents the details of the methods of a pilot field study that was conducted at the University of Canterbury in October, 2018. The first phase of the study was a walk-through energy audit of the building, followed by monitoring of the building areas of study. The second phase of the study was the assessment of occupant AHB. These two phases are described in subsections 2.1 and 2.2. The methods used to analyze the collected data are detailed in section 2.3.

2.1. Building Evaluation
Field research on AHB and thermal comfort with on-site temperature measurements was carried out in single-occupant offices on a top floor of a university campus building in Christchurch, New Zealand. The testing environment is displayed in Figure 1.
Firstly, a walk-through energy audit was conducted. The analysis covered the general building configuration and a brief review of the energy consumption. Building envelope materials and their condition are of special interest to our study, thus were observed in detail. Secondly, indoor temperature, relative humidity and air speed were measured. Lascar EL-USB-2 Data Loggers were used to measure the indoor temperature and relative humidity during the study period. The accuracy of the equipment was +/- 0.3°C and +/- 2.25 %RH, respectively. The indoor air speed was measured in offices prior to the study with a Kanomax A531 anemometer with an accuracy of +/- 0.015 m/s. To include possible effects of the building orientation on behaviour, the studied offices were divided by thermal zones. Two main thermal zones included the offices located on the North-West (NW) and on the South-East (SE) sides of the building, respectively. Two long blocks along the length of the building were considered as the thermal zones of interest. Geometrical irregularities were assumed negligible and corner offices were not included in the zones. The floor plan and orientation of the offices are shown below, in Figure 2.

![Floor plan of the office floor](image)

**Figure 2.** Floor plan of the office floor.

### 2.2. Assessment of occupant AHB

The study was conducted during three consecutive heating-peak days in October, with a total of 26.8 heating degree days (HDD 18°C). Twenty six offices serviced by the university central heating system were studied. The heating system uses medium temperature hot water (MTHW) that comes from a centralized coal-fired boiler, then is fed to the building from the university district heating system and is finally distributed to individual wall radiators located in each office. The radiators were turned off to assess personal AHB under the resulting change in indoor environment, i.e. colder temperatures than would be experienced with radiator heat on demand. Surveys, diaries and interviews were used to collect the data on self-reported behaviour and user perceptions. The duration of the study was 72 hours, chosen for cold conditions in autumn, in Christchurch.

#### 2.2.1. Study Design.

The wall radiators in the offices were turned off for 72 hours and the indoor temperature was monitored with the aid of data loggers; the indoor temperature and relative humidity were measured every 30 minutes. Participants were allowed to use various alternatives to restore their thermal comfort if they felt the temperature was unpleasant, they were asked to record in a diary which adaptive action was taken and when. Examples of alternatives for restoring thermal comfort that were given to the participants were:

- Wear an additional clothing item, e.g. sweater, overcoat/jacket, gloves, scarf, hat, blanket
- Open the blinds to let in the sun
- Perform physical activity, e.g. walk, and stretch
- Use an electric heater provided

Following the 72-hour period, the participants had a semi-structured interview where they were asked questions to evaluate their experience. The interview followed the open-ended question “Did you have any thermal comfort issues?”. The purpose of this essential question, followed by further questions if
applicable, was to identify the trigger thermal sensation for taking adaptive actions and whether these actions resulted in the desired effect. Physical aspects such as clothing and state of the windows and heater were observed during the interview and later interpreted by the researcher.

2.2.2. Resources. Participants: Seventy four invitation letters were sent to academics and staff in the Mechanical/Civil building of the University of Canterbury along with a consent form. A total of 26 respondents were part of the study. All the participants performed sedentary work while in their offices and wore seasonal clothes. Work schedule was from 9am to 5pm. The sample was representative of naturally ventilated office buildings. The protocol received approval from the UC Human Ethics Committee (HEC 2018/43/LR-PS). Survey instruments: A diary template was provided to the participants to record AHB during the study period. The fields required information about the time of the diary entry and the description of actions taken to recover thermal comfort. Examples of alternatives for restoring thermal comfort were prompted at the bottom of each diary sheet. The semi-structured interview was guided by standardized open-ended questions about thermal comfort and the operation of the heating system; accompanied by observation, audio recording of comments and clarification of diary entries, if applicable.

2.3. Analysis
A combination of qualitative and quantitative data analysis was applied to evaluate the AHB of each participant. Subjective data from diaries and interviews was coupled with objective data, i.e. the individual room temperature. Written diary entries, direct observations and recorded verbal comments were analyzed to gain understanding of the current behaviour and adaptive actions taken to maintain or recover thermal comfort. From the interview, answers on the effectiveness of such actions produced statements for qualitative analysis of AHB. The algorithm for characterization of the sample is shown in Figure 3.

![Algorithm for characterization of the sample](image-url)

**Figure 3.** Algorithm for characterization of the sample.
From the results of the survey and the temperature data, the participants were categorized into main and sub categories. Some participants reported no thermal comfort issues. There was an outlier category named I1 which is representative of participants who did not experience thermal comfort issues and whose room temperature did not drop below 20°C. Participants who did not experience thermal comfort issues, but whose office temperature did drop below 20°C were grouped into category A2. The remaining categories are for participants who did report experiencing thermal comfort issues. Participants with thermal comfort issues who took no action were classified as category B1. Of the participants with comfort issues who reported taking action, some reported recovering thermal comfort (these were classified as A1) and some reported not recovering thermal comfort (these were classified as B2). A combination of physical factors resulted in a given indoor effective temperature that was measured.

The factors considered in the qualitative/quantitative analysis were: building features (materials, orientation), heat gain (equipment, lighting, occupancy, occupant characteristics, solar gains, effect of adjacent heated spaces), heat loss (heat-transmitting areas and infiltration), and weather. Relative humidity was proven to stay below 60 percent in the studied location during working hours. Indoor air velocity was measured in sample offices, it was within the range considered as still air (avg. 0.1 m/s). These two factors were considered to have negligible effect on comfort for this study [15]. Hence, dry bulb temperature was the governing reference during the monitoring stage. Physiological factors such as age, metabolic rate, clothing, sex, food, health and acclimatization were recognized but not analyzed in detail. All the above-mentioned factors determine the effectiveness of thermal responses to reestablish the “comfort” temperature (at which the organism has already adapted to) from a “trigger” temperature (at which the individuals perceive the stimulus as unpleasant and in most of the cases decide to take an adaptive action).

For the analysis of the temperature distribution, each indoor temperature data point was subtracted from a base temperature of 20°C and then multiplied by the time interval at which the data was recorded, in this case 0.5 hours. The sum of the absolute products was used in a similar manner to Heating Degree Days to rapidly identify offices with low thermal capacitance. A base temperature of 20°C was selected as a comfort temperature accepted by the ASHRAE Standard 55-92. This new metric is called Cumulative Temperature Change Hour (CTCH); its mathematical expression is presented in Equation 1.

\[
CTCH = \int_{t=7:00}^{18:00} (20 - T(t)) \, dt = \sum_{n=1}^{N} (20°C - T_{i,n}) \Delta t
\]

Where Ti is the office air temperature (in °C), Δt is the time interval between temperature measurements (in hours), and N is the number of temperature measurements (n) during working hours in one day. The interview contained the question: “How do you normally operate the heating system control in your workspace (office) during cold weather?” Five flashcards with alternatives showing different levels of control were randomly presented, they produced answers in a scale from 1 to 5. The answer choices read: “I don’t ever change the setting (always off)”; “I don’t ever change the setting (always on)”; “I turn it up when I am cold and down when I am warm”; “I seldom adjust the control”; and “I don’t know / I can’t control it”. Each participant was given the opportunity to give further explanation of the selected answer, which served as a way to understand the causes for the selection.

3. Results
Following the algorithm to categorize the participants, two cases were excluded due to insignificant temperature drop. As the indoor temperature was unchanged after the reduced heating service, the occupants did not have the need to adopt AHB. Thus, they were binned in Group I1 and excluded from the sample. A total of 26 participants conformed the cohort and were binned in either Group A or Group B. Individual AHB reported by participants in the sub categories A1 and B2 during the 72-hour period is depicted in Figure 4.
Eighteen participants were binned in subgroup A1, while three were assigned to A2, four to B1, and one to B2. Two participants in Group A showed signs of over-adjustment as they described the experience of reduced heating services as enjoyable and reported enhanced performance at work. The level of agreement to the 5-point scale Likert statements “During the winter, my office is too cold regardless of how I operate the radiator” and “During the winter, my office is too hot regardless of how I operate the radiator”, revealed that one of every three users was not satisfied with the thermal office environment prior to the study, as presented in Figure 5, below.

The average indoor temperature of the NW-side offices was 20.24°C and the average indoor temperature of the SE-side offices was 19.72°C during the 72-hour study period. Users of the offices on the NW-side of the wing perceived higher solar radiation compared to those in SE-facing offices. 30% of the NW-side office users and 18% of the SE-side office occupants strongly agreed on the statement “During the winter, my office is often too hot regardless of how I operate the radiator”. Four participants included comments about drafty windows in their diaries, as initiators of energy-intensive actions. Other verbal comments arising from the interview revealed peculiarities of the studied system. For example,
five respondents evaluated the building envelope conditions as inadequate. The distribution of the participants along the two thermal zones is depicted in Figure 6. Parenthesis shows the number of participants in each sub-group.

![Figure 6. Distribution of participants by group and by thermal zone.](image)

Individual responses to thermal discomfort revealed that most of the participants in subgroup A1 started adopting passive measures (e.g. extra clothing) as soon as they perceived a temperature drop or drafty windows; and then decided to use an electric heater when they felt the need to heat the office space. The temperature at which participants decided to use an electric heater ranges from 18 to 19°C for Group A, and 19 to 20 °C for Group B. Most participants did not allow a long-lasting indoor temperature drop below 19.2°C. Diary entries indicated that most participants in Group A preferred to follow a certain sequence of actions e.g. sweater – blanket – electric heater; whereas most participants in Group B skipped the use of passive measures and chose to use the electric heater earlier than those in Group A. One in four A1 users mentioned draftiness as a trigger to use the electric heater. Most of NW-side users reported high solar incidence independently of the season. The distribution of hourly temperature for the sample is shown in Figure 7 for one working day, and the CTHC values are shown in Figure 8.

![Figure 7. Number of (working) hours for different room temperatures.](image)
Figure 8. CTHC for one day, during working hours.

The highest values of CTHC for the sample corresponded to participants in subgroup A1, followed by B1, then B2, and finally A2. CTHC and window orientation for occupants that took effective actions (A1) and for those who didn’t (B1), are presented in Figure 9.

Figure 9. CTHC by window orientation.

Observations and comments on preferred settings and normal operation of the heating equipment revealed that 42% of the occupants had low control over the operation of the heating system control. Oral statements, such as “they (facilities management) put it (heating) off and back on when necessary”, were counted for this estimation. 35% of the sample said that they “never adjust the control”; an equal percentage of participants said they would “adjust for comfort”, and 31% of the sample said that they “seldom adjust the control”. 15% participants were not aware that they could control the radiator valve; see Figure 10 for a summary. Most of the participants in category A1 reported frequent control adjustment. Respondents who reported no control over the radiator justified their habitual operation with either lack of awareness/familiarity or difficult access to the controls although it was checked that all the participants had the opportunity to change the settings. 27% of the occupants reported window
opening during heating seasons; some for ventilation purposes, others to release the excess heat especially during sunny afternoons in winter.

![Figure 10. Habitual operation of heating control.](image)

The analysis of the demographics of the population in this study showed that most female participants took immediate action after reporting discomfort. 30% of the men in Group B did not take effective measures to recover their comfort. Statement examples that explain a lack of thermal adaptive actions are: “it was cold but bearable” and “I had the intention to use the heater but I didn’t”.

4. Discussion
The observed responses display two characteristics of effective thermal adaptation in sub group A1: 1. Incremental action implementation in response to temperature drop, and 2. Effective recovery of thermal comfort by making use of available opportunities. The fact that some of the office workers in A1 did not report wearing extra clothing may be due to habits already formed and not considered worth reporting. However, these personal actions were observed during the study and they were counted as AHB. Participants binned in Group A featured higher tolerance to colder environments, compared to those in Group B, possibly due to either their natural acclimatization propensity, i.e. physiological and psycho-social factors, and/or due to the adoption of personal adaptive measures. The assessment of CTCH showing the highest values for A1, followed by B1, then B2, and finally A2, suggests that some office users in A1 were exposed to higher thermal discomfort compared to those in other groups, possibly due to the low thermal capacitance of their offices. Notwithstanding, by performing AHB, A1 users could effectively recover thermal comfort. Conversely, participants in B1 decided to not take any actions despite sustained periods of thermal discomfort. The temperature profiles and reported AHB of the occupants in A2 revealed that not reporting issues is matched with minimal temperature drop in time, and under similar environmental conditions, the participant in B2 could not recover comfort despite taking actions. AHB for subgroups A2 and B2 can be explained by individual physiological factors, once physical conditions for thermal discomfort were discarded as the prevailing cause. Only one participant could not adapt well despite the several efforts to recover thermal comfort. The user’s office was checked for sources of local discomfort, with none found. Individual factors not included in the scope of this study are assumed to be the cause of dissatisfaction in this particular case. Further research in this area can help identify psychological factors that prevent users to actively recover comfort when exposed to indoor environmental variations, for example, the lack of action in group B1.

Most participants stayed close to the lower limit of the ASHRAE thermal comfort range for winter. There is no clear differentiation between groups and sides of the building although solar incidence was mentioned by NW-side office users in their narratives. However, perceived draftiness was a definite trigger for action taking. Since most participants in group A1 reported habitual adjustment of the heating controls, it can be inferred that already acquired habits reinforce effective thermal adaptation.
Identifying the patterns and triggers for AHB on a case-by-case basis is necessary, especially as AHB can significantly influence to the building’s energy consumption.

Thermal sensitivity varies according to individual characteristics such as age, metabolic rate, sex, food intake, etc. as studied in depth by Fangar [16]. Although it has been found that women are more sensitive to temperature changes [17], female participants in this study demonstrated higher adaptive behavioral features compared to men as demonstrated by Indraganti, et al. [18]. This is, female participants acted as soon as they felt uncomfortable and most of them accomplished the objective of those actions. Notwithstanding, this action taking may have implied a higher energy consumption compared to the provided with the original setting. In most cases, the heater (once turned on) was only turned off at the end of the day. This can be explained by the difference in motives inducing such actions. For example, the heater is turned on when feeling cold and turned off at the end of the day, even if the upper limit of comfort temperature was reached or surpassed. This phenomena can be attributed to: (i) the reversal of adaptive actions after the source of discomfort fades [19], and (ii) habits of controls operation. Other non-physical parameters such as sense of connection to the external environment, explaining opening the windows even when it is cold outside, for example, were also noted as imminent values for adaptation processes in thermal comfort. There were two types of thermal adaptation: active and internal, as suggested by Zeidner and Endler [20]. These forms of response depended on the way the individuals perceived the situational constraints and whether they evaluated the constraint from a practical perspective. Those who performed active adaptive strategies, e.g. used a heater, showed signs of an orderly set of adaptive measures, compared to the ones who internally adapted to the environmental stimuli, i.e. participants who acknowledged a temperature difference but did not act on it.

5. Conclusions and Further Research
Occupant Adaptive Heating Behaviour was assessed in an office building as a pilot case study. The emphasis of this research is on the energy-use implications of AHB, its trigger sensations of discomfort, and the effectiveness of adaptive actions. The pilot assessment was successful in identifying the behavioural patterns within categories. The research scope at this first stage was limited to assessing the occupant behaviour in reduced-energy heating settings. The methods used in this pilot study to assess occupant AHB, are informative to future research on how to link environmental conditions to user behaviour in office settings, through the analysis of qualitative and quantitative data. Further research will evaluate the nature of the AHB, i.e. passive or energy intensive, the trigger points for the actions taken based on weather data, and the socio-cognitive factors of influence on AHB.

References
and acoustics.


