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# My apartment is cold! Household perceptions of indoor climate and demand-side management in Sweden

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ABSTRACT

Space heating represents a major share of a households' total energy consumption and related $CO_2$ emissions. An approach often suggested to improve both the environmental and economic performance of the energy system is demand-side management. However, there has been little research into how households perceive load shifting in space heating. This paper evaluates the thermal perception among tenants in 33 multi-residential buildings connected to district heating in Sweden. Centrally controlled load shifts were applied in eight of these buildings during a two-week trial in early winter. The participants recorded their thermal sensation and thermal satisfaction in a diary, supplemented by opening and closing surveys. The results indicated that indoor temperatures at home were generally experienced as being low, especially in the morning. Control over heating was regarded as insufficient. No statistically significant difference in thermal sensation and satisfaction between days with and without load shifts was identified. However, after the trial, significantly fewer participants than before were willing to accept greater temperature variations to save energy. The study further highlights four factors that may influence the perception and acceptance of demand-side management in residential space heating: (1) set indoor climate conditions, (2) timing and magnitude of load shifts, (3) individual control and (4) communication.

## 1. Introduction

Building-related emissions rose to an unprecedented level in 2018, representing 28% of global energy-related $CO_2$ emissions when including indirect emissions from upstream power generation [1]. In the European Union, 26% of final energy consumption in 2018 was attributable to the residential sector, of which space heating accounted for almost two-thirds [2]. Renewable energy sources covered just 27% of the energy demand for space heating [2].

The transition, from energy systems based largely on fossil fuels to 100% renewable energy, presents the challenge of integrating a more fluctuating energy supply [3]. This motivates the introduction of demand-side management strategies to create more energy flexibility in buildings through load shifting, peak shaving and valley filling [4]. One approach is to utilise the thermal inertia of buildings to store energy. This enables heating energy use to be shifted from critical periods (involving high demand, costs and $CO_2$ emissions) to more favourable periods (when a greater share of renewable energy sources is available [5,6]).

According to Strengers [7], much of the previous research into demand management strategies has focused on the effectiveness of limiting energy use during peak hours but has overlooked how increasing comfort expectations give rise to, and are influenced by, these strategies. Consistent with other researchers, Strengers determined that comfort expectations are malleable and constantly evolving through, for instance, the introduction of new technologies, infrastructures and regulations [7]. Instead of taking unsustainable meanings and expectations of comfort for granted, Chappells and Shove [8] argued that *"the relation between comfort, climate change and environmental sustainability could and should be the subject of explicit social, technical and political debate"* (p. 33). Furthermore, several researchers have highlighted the need to improve understanding of residents' thermal comfort requirements [9], their willingness to accept external control of the indoor environment [10] and to adapt their energy consumption patterns [5].

The overall aim of the study presented in this paper was to develop a better understanding of the perception of indoor temperature conditions at home and demand-side management in residential space heating, from the residents' perspective. The following research questions were posed: (1) How do participants perceive their indoor climate at home and their ability to control it? (2) To what extent does demand-side

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management in space heating affect participants' thermal perception? Besides addressing these research questions, the study served as a pilot aiming to evaluate a mixed methodology for investigating residents' perspectives on indoor climate and demand-side management at home. The study collected mainly quantitative data through a diary and two surveys and respondents were able to leave comments.

The paper starts with the background to the study in Section 2, including a description of the terminology used in the paper, district heating in Sweden, previous research into demand-side management in district heating systems, thermal perception and heat-related practices. Section 3 explains the research approach and methods used in the study. Section 4 presents the research findings, starting with participants' attitudes to heating and energy use at home and followed by an exploration of their thermal perception before, during and after the trial. A discussion is provided in Section 5, relating to previous research regarding thermal perception, heat-related practices and demand-side management. The paper's conclusions appear in Section 6.

## 2. Background

Table 1 provides a list of terms used in the paper and their meanings.

**Table 1**
Terminology used in this paper.

| Term | Explanation |
|---|---|
| thermal sensation | A subjective measure of how the participants experienced their indoor temperature. In the diary, this was measured on a scale from *cold* to *warm*. |
| thermal satisfaction | A subjective measure of how satisfied the participants were with their indoor temperature. In the diary, this was measured on a scale from *very dissatisfied* to *very satisfied*. |
| thermal perception | In this paper, *thermal perception* is used as a collective term incorporating thermal sensation and thermal satisfaction. |

### *2.1. District heating in Sweden*

In Sweden, 93% of all multi-residential buildings were in 2014 connected to district heating [11]. The largest share of the energy sources used for district heating comes from biomass, followed by waste incineration and excess heat from industry. The emissions of greenhouse gases from district heating and electricity production have decreased and were 24% lower in 2018 compared to 1990 [12]. In 2015, only 7% of the district heating energy supply came from fossil fuels [11]. Thus, $CO_2$ emissions related to space heating are over 80% lower in Sweden than in other European cities which use natural gas and fuel oils to heat buildings [13]. District heating, as an important part of smart thermal grids, may help create flexibility in the energy system, recycling heat losses and integrating fluctuating renewable energy sources [3].

In climate conditions with small variations in outdoor temperature, peak demand in district heating systems often takes place during mornings and evenings [14]. This is due to the greater demand for hot water during these periods. By contrast, in climate conditions with major outdoor temperature variations between day and night, peaks in heat demand often occur at night [14].

### *2.2. Previous research into demand-side management in district heating systems*

A small number of experimental studies have investigated the potential for achieving greater flexibility in heating demand in residential buildings connected to district heating. One study assessed two concrete buildings in Finland during the winter of 2002–2003; an office building and a service building for senior citizens [15]. This trial showed that the heat load could be lowered by 20–25% for a period of two to three hours, with a resulting temperature variation of up to 2 °C. In a field test by Wernstedt et al. [16], an agent system was installed in 14 apartment buildings in a district heating network in Sweden, with the aim of reducing peak demand through peak cutting. During the test, the total energy consumption was reduced by 4% in the area without any detected reductions in measured indoor temperature. However, based on their results, the authors estimated that savings of more than 10% in total energy consumption would be possible, depending on building characteristics. Kensby et al. [14] evaluated the thermal energy storage potential of five residential apartment buildings in Sweden by introducing several periods of charging and discharging throughout the day. Based on results from the building with the greatest temperature variation (among those classified as heavy buildings in the test), it was found that indoor temperature variations of less than ±0.5 °C were achievable with heat storage of 0.1 kW h/m$^2$. Another study evaluated 13 homes in a residential apartment building in Denmark and demonstrated that energy use during peak hours could be cut by 85% with little impact on indoor temperature levels and total energy consumption [17].

These studies, however, did not investigate the residents' experience of the indoor climate or their opinions regarding temperature deviations caused by the heating control applied during the tests. However, Kensby et al. [14] and Wernstedt et al. [16] did receive information from the landlords indicating that the frequency of complaints from tenants did not increase during the test periods. The following two studies focused more strongly on residents' experiences and practices during the trials.

Sweetnam et al. [9] conducted a field study in the United Kingdom that aimed to improve the load factor in a sample of 28 dwellings of different typologies connected to a district heating network, by introducing demand-shifting technology. In this trial, the load factor increased from 0.29 to 0.44, which also resulted in a slight (3%) increase in energy demand. Participant feedback was collected during the trial, which revealed some concerns regarding the unusual operation of the heating system, although only modest alterations in indoor temperature were caused by the demand shifting. Larsen and Johra [10] conducted a qualitative study that explored households' engagement with smart home technology and the potential for such technology to enable load shifting in 16 Danish homes of different typologies connected to district heating. They found that although the introduction of smart home technologies offered the participants a convenient means of controlling the indoor temperature, this often resulted in higher indoor temperature setpoints and higher requirements regarding indoor comfort. Additionally, a common practice among participants was to open windows at different times during the day, with many also preferring to have a cold bedroom. These findings highlight possible challenges to increasing flexibility in heating demand. Furthermore, the participants were generally sceptical about operating the feature of increased heating flexibility themselves. They preferred this to be managed either automatically through machine learning or centrally controlled by a third party, such as the building manager, provided it did not compromise their comfort [10].

### *2.3. Previous research into thermal perception and heat-related practices*

Hansen et al. [18] analysed heat-related practices in relation to building characteristics for households living in detached single-family houses in Denmark. They used a questionnaire and administrative data. They found that residents in more energy-efficient homes tended to maintain higher indoor temperatures than residents in less energy-efficient ones; this helps explain the difference between predicted and actual energy consumption often seen in newer buildings. They also found that, regardless of the energy efficiency of the houses, residents with higher education and women tended to wear warmer clothing during winter. Additionally, the more educated group tended to adjust thermostats more often. This was also the case for residents with a partner as well as immigrants, or descendants of immigrants. In the same study, Hansen et al. [19] found that women and older residents tended to value a comfortable home indoor environment more highly than did other groups. Their results also identified a relationship between the value placed on homely comfort and the amount of energy used for space heating; higher value was related to higher energy use. Previous research by Karjalainen [20] indicated that women prefer higher room temperatures and also tend to feel uncomfortably cold or hot more often than men. Similar results were found by Henning [21], in a study that included Swedish tenant households with Somali and Kurdish backgrounds.

Through a diary study and interview study of Swedish households, Renström and Rahe [22] found that residents have varying preferences for heating and often feel limited in their control over the indoor temperature. To improve thermal comfort, the participants used varying techniques that did not necessarily involve any interaction with the heating system. Common strategies were to adjust clothing or blankets, move or change body posture, open or close windows, drink something warm or cold and take a shower [22]. The study by Henning [21] found that insufficient heating and lack of control over the indoor temperature resulted in some tenants buying extra radiators, starting to use their oven as an extra heater, using thick carpets as insulation from cold floors or closing the ventilation.

In a survey study in the Netherlands, Guerra Santin [23] analysed behavioural patterns and identified different user profiles related to heating energy consumption at home. The results indicated that, in relation to other groups, seniors tended to maintain higher temperatures at home for longer periods. However, their energy consumption was generally lower than that of families and high-income couples. The higher energy consumption of families was related to their need for more space and greater use of heavy appliances. High-income couples tended to want convenience at home and were less concerned about their energy use. The lowest energy consumption was found in the user group of singles and low-income couples; their behaviour was less related to temperature comfort or intensive use of appliances and space.

Another study by Sovacool et al. [24] identified how conflicts regarding space heating may arise between different members of the same household, as well as in relationships that go beyond the home. The identified forms of thermal conflicts were between (1) parents and children, (2) spouses or partners, (3) roommates, (4) hosts and guests and (5) tenants and landlords. Such conflicts may originate in different heating preferences, activities connected to using the heating system or values regarding heating and energy consumption [24].

## 3. Research approach and methods

The study was conducted during November and December 2019 in multi-residential buildings connected to district heating in Malmö (in southern Sweden). The research was divided into three phases, as described in Table 2.

**Table 2**
Overview of study phases and activities.

| Study phase | Activity | Purpose |
|---|---|---|
| 1 | Registration and initial survey (S1) | - Collect demographic information about the participants<br>- Collect general opinions regarding indoor climate and thermal energy use at home<br>- Create groups for subsequent phases of the study |
| 2 | Two-week trial, including:<br>- Power control applied to district heating in selected buildings<br>- Diary study | - Collect data regarding participants' perception of indoor temperature and load shifting in real time |
| 3 | Closing survey (S2) | - Compare opinions regarding indoor climate and thermal energy use at home after the trial with the results from S1<br>- Validate results of the diary study |

This research design was chosen to enable investigation of participants' thermal perception and their opinions of the indoor climate before, during and after load shifting was introduced. The diary tools facilitated real-time data collection, which helped make the reported data as accurate as possible. Combining the diary study with two surveys allowed the results to be compared and searches made for differences before and after the trial. The surveys also enabled validation of the diary study results.

### 3.1. Recruitment of participants

Participants were recruited from buildings owned by the municipal housing company, which rents out homes to approximately 23,000 households. At the time, 84 of their buildings were connected to a Customer Energy and System Optimisation (CESO) system (further described in Section 3.2), managed by the local energy provider. These buildings were therefore targeted for the study.

A limitation of the recruitment process was that the researchers were not allowed to contact the residents personally (by email, for example). Instead, flyers containing study details were deposited in tenants' mailboxes and posters were placed in the entrances of the 84 buildings with an invitation to sign up for the study via a weblink. In appreciation for their involvement, cinema tickets were promised to all participants who completed the study. This small compensation was unlikely to have had much effect on the response rate.

A total of 93 participants from 33 buildings registered for the study and completed the initial survey (hereinafter referred to as S1). The low response rate was likely due to the limitation of not being able to contact the residents more directly than through printed material.

Power control could be applied in 12 of the buildings. Prior to the trial, the participants living in these 12 buildings were randomly divided into groups A and B, with participants of both groups represented in all buildings. The difference was that group A received notifications in advance of the load shifts but group B did not. Notifications were sent approximately 30 min before the shifts. If a shift was planned during the night, the notification was sent at 8:00 PM on the evening before. The message read: *"Today, the temperature in your apartment will be lowered/raised slightly between XX:XX and XX:XX"*.

The participants in the remaining buildings without power control were included in group C, which functioned as a control group. However, during the trial, power control could only be applied in eight of the 12 buildings initially belonging to groups A and B. Therefore, participants previously in group B but found to be living in one of the buildings without power control were included in group C for the analysis. Participants who previously belonged to group A in these buildings were assigned to a new group, AC, because they received notifications of the load shifts during the trial, despite no such shifts actually being applied in their buildings (see Table 3).

The properties of the eight buildings with power control are summarised in Table 4. These buildings were home to 40 participants in total from S1, of which 20 belonged to group A and 20 to group B. Although refurbishments are only reported for three of the buildings, it is likely that smaller changes have also been made to the remainder, such as replacing windows. For the remaining 25 buildings, information about construction year was missing for two and the rest were constructed

**Table 3**
Participant groups.

| | Group A | Group B | Group C | Group AC |
|---|---|---|---|---|
| Load shifting during the trial | Yes | Yes | No | No |
| Notifications sent before load shifting was applied | Yes | No | No | Yes |
| Reminder sent if no diary entry had been made that day | Yes | Yes | Yes | Yes |

**Table 4**
Information about study buildings *with* heat power control.

| Building | Year of construction | Year of refurbishment | Storeys | Apartments | Total living area ($m^2$) | Energy performance, primary energy* (kWh/$m^2$ and year) | Participants (S1) |
|---|---|---|---|---|---|---|---|
| 1 | 1958 | – | 16 | 143 | 8333 | 103 | 8 |
| 2 | 1958 | – | 9 | 180 | 11,930 | 131 | 4 |
| 3 | 1973 | 2002 | 6 | 492 | 12,678 | 131 | 13 |
| 4 | 1962 | – | 9 | 90 | 5525 | 98 | 6 |
| 5 | 1962 | – | 8 | 80 | 5024 | 184 | 2 |
| 6 | 1959 | 1989 | 4 | 97 | 6927 | 122 | 2 |
| 7 | 1959 | 1989 | 4 | 71 | 4804 | 120 | 2 |
| 8 | 1949 | – | 3 | 21 | 1301 | 143 | 3 |

*Includes energy for heating, hot tap water, air-conditioning and the building's property electricity. Data retrieved from the Swedish National Board of Housing, Building and Planning [25].

between 1930 and 2015, with a median construction year of 1959. This is a wide range and may contribute to differences in indoor climate between the buildings. Heating was included in the apartment rent for all buildings.

An overview of the demographic data of the participants in the different study phases and participant groups is shown in Table 5. As the table shows, the share of female participants was slightly lower in group A compared with the other groups. No participants were 85 or older, but all age groups from 0–17 to 75–84 were covered, with the greatest share in the age group 25–34 (38% in S1 and S2).

To capture information regarding cultural background, the participants were asked which languages were spoken at home apart from Swedish. Among the respondents who reported using other languages at home, they most commonly reported speaking languages originating in European or Middle Eastern countries.

Furthermore, the highest number of participants reported spending 2–3 days per week at home during daytime (41% in S1 and 46% in S2), followed by those reporting spending 6–7 days per week at home during daytime (31% in S1 and 38% in S2). Only small variations were seen when comparing the groups.

### 3.2. Technical setup

The eight buildings in which participants in groups A and B resided, as presented in Table 3, were all equipped with a CESO system managed by the local energy provider. CESO utilises the natural thermal inertia of the buildings to enable load shifting over short periods of time. Indoor temperatures are allowed to change by ±0.5 °C, which typically allows for a 75% power reduction for two hours or a 25% power reduction for six hours. A warning is given by the system if a planned load shift is calculated to impact the temperature by more than 0.5 °C. However, it does not measure *actual* indoor temperature changes due to load shifts. The aim of the CESO system is to reduce peak generation by approximately 5–10% of the nominally installed heat output of the district heating system.

**Table 5**
Information about study participants in the different study phases and participant groups.

| | S1 | Diary study | S2 |
|---|---|---|---|
| Number of participants | 93 (A: 20, B: 20, C: 43, AC: 10) | 48 (A: 12, B: 7, C: 23, AC: 6) | 72 (A: 15, B: 15, C: 32, AC: 10) |
| Female participants (%) | 57 (A: 45, B: 60, C: 58, AC: 70) | 58 (A: 50, B: 71, C: 57, AC: 67) | 58 (A: 40, B: 67, C: 59, AC: 70) |
| Participants over 65 (%) | 15 (A: 20, B: 10, C: 14, AC: 20) | 17 (A: 25, B: 0, C: 17, AC: 0) | 15 (A: 20, B: 7, C: 16, AC: 20) |
| Participants speaking languages other than Swedish at home (%) | 32 (A: 5, B: 30, C: 47, AC: 30) | 25 (A: 0, B: 14, C: 43, AC: 17) | 33 (A: 7, B: 36, C: 45, AC: 30) |

Table 6 presents the control scheme for load shifts during the trial. A negative number indicates a power reduction and a positive number indicates a power increase. This control scheme is not a representative schedule for peak-hour demand reductions, which would typically include power reductions of 25–50% between 6:00 to 9:00 AM and 4:00 to 7:00 PM. Rather, the control scheme applied during the trial was a test with the purposes of evaluating the power control functionality of the buildings and analysing the effect of the power output. Naturally, the low number of applied load shifts (only one in building 5, three in building 1, and five in buildings 2–8) limits the opportunities for evaluating participants' thermal perceptions in relation to load shifts. However, it did allow the methodology of this pilot study to be tested.

### 3.3. Surveys

In both surveys, the participants were asked to opine on a number of statements regarding thermal energy use at home, using a Likert scale. Likert scales were also used in several other questions, some of which were repeated in S2 to identify any changes in comparison. Comments could be given at the end of the surveys. An overview of the questions with Likert scales is shown in Table 7. Answers in the rightmost column (marked –) were excluded from the analysis.

The scale, from *too cold* to *too warm*, used in two of the questions below may have biased the results slightly because the participants may have experienced the temperature as cold even though they did not find it *too* cold. Therefore, it would have been better to use a scale from *cold* to *warm* and combine it with an additional question that separately measured temperature satisfaction. This was done in the diary (see Section 3.4).

### 3.4. Diary tools

During the trial, the participants could use either a web-based diary tool (hereinafter referred to as the *digital diary*) or a paper diary to report their perception of the indoor temperature at any time of the day. The digital diary enabled participants to either report their current thermal perception or make a daily summary at the end of the day. Current temperature perception reports comprised five questions: (1) How are you experiencing the temperature right now? (2) How satisfied are you with the temperature in your apartment right now? (3) In which part of the apartment are you right now? (4) What are you doing at the

**Table 6**
Control scheme for load shifts during the trial.

| Date | Power control | Time | Applied in buildings |
|---|---|---|---|
| 2019–11–18 | −50% 1 h | 9:00 AM–10:00 AM | 2–8 |
| 2019–11–20 | −50% 1 h | 10:00 AM–11:00 AM | 2–8 |
| 2019–11–22 | −50% 3 h | 1:00AM–4:00 AM | 5 |
| 2019–11–27 | −100% 0.5 h | 1:00 PM–1:30 PM | 1–8 |
| 2019–12–01 | −25% 3 h | 3:00 AM–6:00 AM | 1–8 |
| 2019–12–01 | +25% 1 h | 6:00 AM–7:00 AM | 1–8 |

**Table 7**
Survey questions with Likert scales.

| Survey | Question | 1 | 2 | 3 | 4 | 5 | – |
|---|---|---|---|---|---|---|---|
| S1 & S2 | Statements (see Table 8) | Strongly disagree | Disagree | Neither agree nor disagree | Agree | Strongly agree | Don't know |
| S1 | How satisfied are you in general with the temperature in your home? | Very dissatisfied | Dis-satisfied | Neither satisfied nor dissatisfied | Satisfied | Very satisfied | N/A |
| S2 | …during the last two weeks? | | | | | | |
| S1 | How do you normally experience the temperature in your home? (morning, daytime, evening and night) | Too cold | A little too cold | Just right | A little too warm | Too warm | Don't know |
| S2 | …during the last two weeks? | | | | | | |
| S1 | Is there a certain part of your apartment that you think is too warm or cold? (bedroom, living room, kitchen and bathroom) | Too cold | A little too cold | Just right | A little too warm | Too warm | N/A |
| S2 | …during the last two weeks? | | | | | | |
| S1 | How often do you experience that you are too cold/warm at home during the summer (April-September)/winter (October-March)? | Never | Rarely | Several times per month | Several times per week | Every day | Don't know |
| S2 | Did you, during the last two weeks, experience the temperature in your home as warmer or colder than usual? | Much colder | Slightly colder | No change | Slightly warmer | Much warmer | Don't know |
| S2 | Did you, during the last two weeks, experience the temperature in your home as better or worse than usual? | Much worse | Slightly worse | Neither better or worse | Slightly better | Much better | Don't know |
| S2 | How often, during the last two weeks, did you experience any sudden temperature changes in your apartment? | Never | Rarely | A few times per week | Every day | N/A | Don't know |

moment? and (5) Do you think that what you are doing affects how you experience the temperature? Additional comments could be added at the end.

The daily summary was divided into four parts of the day: *last night* (8:00 PM–6:00 AM), *morning* (6:00 AM–12:00 PM), *afternoon* (12:00 PM–5:00 PM) and *evening* (5:00 PM–8:00 PM). The participants were asked to answer two questions (adapted from the presented previously questions 1 and 2) for each period of the day during which they were at home. A reminder to make a daily summary was sent out at 8:00 PM each evening of the trial period to all participants who had not reported on their current temperature perception during the day. The digital diary is shown in Fig. 1.

The paper diary was given as an option to prevent the exclusion of residents without smartphones, or those who would find using the web-based diary complicated. The design of the paper diary was based on the digital diary and involved the same questions; this was to ensure that results from both data collection tools were comparable. The paper diary is shown in Fig. 2.

### 3.5. Analysis

Data from the two surveys was analysed in Microsoft Excel and IBM SPSS Statistics. Results from questions repeated in S2 (from S1) were analysed using the Wilcoxon signed-rank test, to evaluate whether any statistically significant differences were evident in opinions before and after the trial period. The Wilcoxon signed-rank test is a nonparametric approach for comparing two related or paired samples [26]. This test was selected because the responses were given in Likert scales and data was thus considered ordinal (nonparametric). Only responses from participants who completed both S1 and S2 were compared in the test. Although responses were treated as ordinal data, averages were calculated to give a simple indication of how much the responses differed. A Wilcoxon signed-rank test was also used to analyse whether any statistically significant difference was evident in temperature perception at

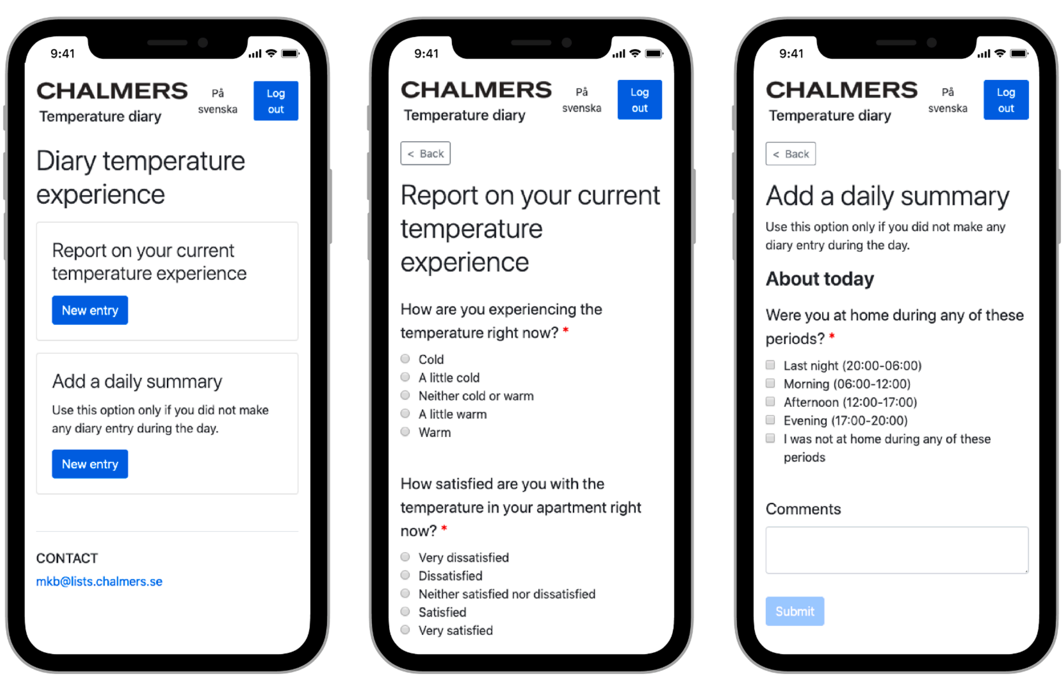


**Fig. 1.** The digital diary home screen (left), with the options to report on the current temperature perception (middle) or submit a daily summary (right).

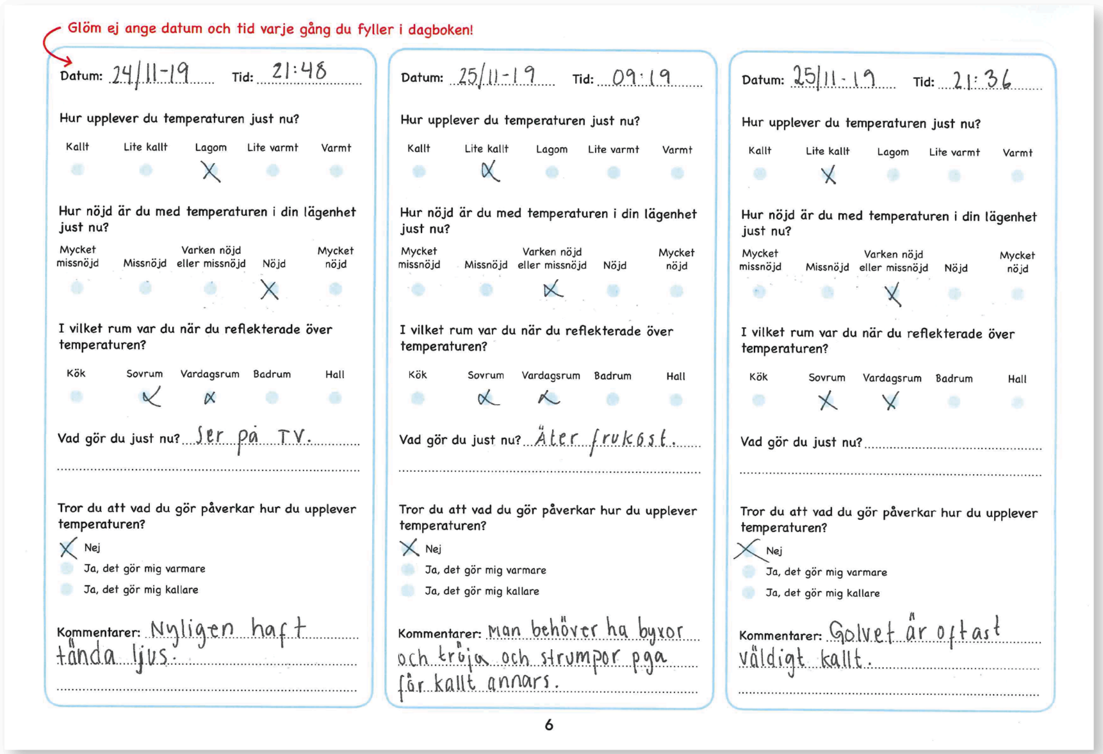


**Fig. 2.** Paper diary for reporting temperature perception, with each column representing one entry.

different times of the day, according to the survey results.

In the analysis of other survey questions, the focus was instead on evaluating potential differences between responses from different participant groups and genders. The responses were again classified as ordinal data but the samples were not related. A Mann-Whitney *U* test (a nonparametric approach for comparing two independent samples [26]) was therefore used.

Data from the digital diary entries, daily summaries and paper diary entries were combined in an Excel file and imported to SPSS. A Mann-Whitney *U* test was used to evaluate potential differences in thermal sensation and satisfaction depending on participant group, gender and the time of the day at which the diary entry was made. The grouping of all diary entries followed the same timespans used in the daily summary previously described in Section 3.4.

Furthermore, to evaluate the potential impact of local weather conditions on the indoor temperature during the trial, a correlation analysis was made between indoor temperature, outdoor temperature and wind speed. The results of all statistical analyses were considered significant for *p* values below 0.05.

Qualitative data from comments in the surveys and diary entries were categorised thematically and then summarised to complement the quantitative data. A few illustrative comments were selected and, if they were written in Swedish, translated to English by the first author.

## 4. Findings

This section presents the participant attitudes regarding heating and energy use at home, which is followed by an analysis of the thermal perception before, during and after the trial.

### 4.1. Attitudes towards heating and energy use at home

Fig. 3 shows the distribution of responses to the statements in S1 (n = 93).

The results of statement 1 shows that most participants considered they did not have enough control over the heating at home, with 71% (n

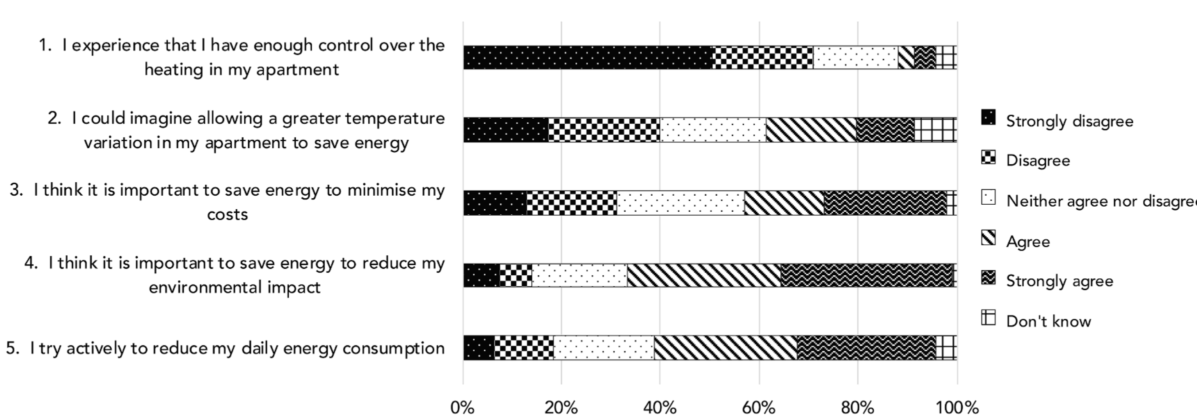


**Fig. 3.** Response distribution in S1 for statements regarding attitudes towards thermal energy use at home.

**Table 8**
Results from the Wilcoxon signed-rank test and mean values for statements regarding attitudes towards thermal energy use at home (*strongly disagree* = 1 and *strongly agree* = 5).

| Statement | Mean S1 | Mean $S1_{S2}$ | Mean S2 | Z | *p* value |
|---|---|---|---|---|---|
| 1. I experience that I have enough control over the heating in my apartment | 1.85 (n=89) | 1.88 (n=68) | 1.99 (n=70) | −1.005 | 0.315 |
| 2. I could imagine allowing a greater temperature variation in my apartment to save energy | 2.84 (n=85) | 2.92 (n=66) | 2.48 (n=65) | −2.471 | **0.013** |
| 3. I think it is important to save energy to minimise my costs | 3.22 (n=91) | 3.25 (n=71) | 3.11 (n=70) | −0.503 | 0.615 |
| 4. I think it is important to save energy to reduce my environmental impact | 3.79 (n=92) | 3.86 (n=71) | 3.58 (n=71) | −1.934 | 0.053 |
| 5. I try actively to reduce my daily energy consumption | 3.63 (n=89) | 3.66 (n=68) | 3.37 (n=71) | −1.470 | 0.142 |

= 66) either disagreeing or strongly disagreeing with this statement in S1. This was confirmed by several comments. Five participants in group C asked for more control of the temperature in their individual apartments. Although radiators usually allow some adjustment, they may already have been set to maximum heat without the participants experiencing getting enough heat. One explained, *"I would have liked to be able to regulate the heat in the radiators myself and then pay for consumption. The change between summer [and] winter is too cold"* (man, group C). Two other examples were:

> *I think it would be good if you could choose yourself how hot it should be because I'm freezing and think it's awful that I pay thousands [of Swedish kronor] to freeze! I might as well sleep outdoors? [...] Personally, I never waste energy and hate it when you let the water run or have hot radiators near an open window. (Man, group C)*

> *In our apartment, there is no opportunity to regulate the temperature at all [...] which can sometimes make it very cold before the heating is turned on; usually it's like that. Right now, for the first time ever, it is very warm in the apartment. (Woman, group C)*

The statement that scored highest was statement 4, *"I think it is important to save energy to reduce my environmental impact"*, with an average of 3.79 and with 65% (n = 61) either agreeing or strongly agreeing. Statement 3, which focused instead on cost savings, received a lower average score of 3.22, with 41% (n = 38) either agreeing or strongly agreeing. Statement 5, *"I try actively to reduce my daily energy consumption"*, scored second highest with an average of 3.63 and 57% (n = 53) either agreeing or strongly agreeing.

Table 8 presents the averages for the statements alongside results from the Wilcoxon signed-rank test. The averages for S1 are presented both in total (S1, n = 93) and for the participants who also completed S2 ($S1_{S2}$, n = 72), so that the same sample in S1 and S2 may be compared.

The only statement that evidenced a statistically significantly different result in $S1_{S2}$ and S2 was statement 2: *"I could imagine allowing a greater temperature variation in my apartment to save energy"*, which had a lower level of agreement in S2 than in S1. Even though the other statements showed no statistically significant difference between $S1_{S2}$ and S2, the trend for all statements except the first one was lower agreement with S2.

A correlation analysis of the responses to statements 1 and 2 in S1 revealed a positive relationship, with r = 0.300 and $p$ = 0.006. This indicates that those who experienced having enough control over the heating in their apartments were more able to imagine allowing greater temperature variations to save energy.

## 4.2. Thermal perception at home before the trial

In S1, the response distribution regarding how satisfied the participants were with the temperature at home was spread. 44% (n = 41) answered that they were either *dissatisfied* or *very dissatisfied*, whereas 29% (n = 27) reported that they were either *satisfied* or *very satisfied*. No statistically significant difference was found when comparing responses from men and women, with the average scores of 2.55 for men and 2.83 for women. However, one respondent in group C noted that indoor temperatures are regulated according to the comfort zone of men, whereas women tend to have a different metabolism and therefore often feel colder.

Regarding thermal sensation at different times of the day, the averages were 2.17 for *morning*, 2.60 for *daytime*, 2.39 for *evening* and 2.41 for *night*. A Wilcoxon signed-rank test found that mornings were perceived as statistically significantly colder and daytime as statistically significantly warmer than other times of the day. During mornings, 67% (n = 62) experienced the temperature as either *too cold* or *a little too cold*, whereas only 6% (n = 6) experienced it as either *too warm* or *a little too warm*.

During the winter, 38% (n = 35) of the respondents reported feeling *too cold* at home every day, 26% (n = 24) a few times per week and 17% (n = 16) a few times per month. Unsurprisingly, these numbers were much lower during the summer season. Similarly, very few experienced being *too warm* at home during the winter season. During the summer, 12% (n = 11) reported feeling *too warm* at home every day, 36% (n = 33) a few times per week and 23% (n = 21) a few times per month.

Four participants belonging to groups A and C commented that there was a major difference between the winter and summer temperatures in their apartments. One explained, *"My apartment is so cold during the winter, especially during the night and I always have extra clothes on and a blanket if I have to sit in the living room"* (woman, group C). Another commented:

> *Every winter so far we have been freezing terribly at home, [with the temperature] often around 18 °C inside. The landlord doesn't care at all. In the summers it can be up to 32 °C indoors, because the ventilation is so lousy. In fact, the apartment is like a rainforest for a few hours after you've taken a shower. (Man, group A)*

The problem of insufficient ventilation or lack of opportunity to air out their apartments was mentioned by four respondents in groups A and C. One explained:

> *When sedentary, I can often feel that it gets too cold but having a blanket or cardigan usually helps. In my apartment I unfortunately only have a very narrow openable window, or two balcony doors that I don't want to leave open when I'm not at home. (Woman, group A)*

Furthermore, two participants in group A complained about insufficient insulation or open valves in the building, which made the indoor temperature susceptible to wind: *"In summer it is too hot with temperatures sometimes up to 35 °C on a normal sunny day. In winter we can have 16 °C in rooms exposed to the wind"* (man, group A). Three participants in group C commented that it was usually very cold at home in the autumn, before the heating is turned on for the winter season.

Regarding thermal sensation in different rooms, the averages were 2.55 for the bedroom, 2.22 for the living room, 2.52 for the kitchen and 2.46 for the bathroom. A Wilcoxon signed-rank test showed that the living room was experienced as statistically significantly colder than all other rooms.

## 4.3. Thermal perception at home during the trial

This section presents the indoor temperatures and weather conditions during the trial. There then follows an analysis of the thermal perception reported in the diary entries, comparing different participant groups and different parts of the day.

### 4.4. Indoor temperatures and weather conditions during the trial

Indoor temperature data was measured hourly in each apartment of the study buildings during the two weeks of the trial. Unfortunately, the data received from the housing company did not reveal which apartments belonged to the study participants and the researchers were not allowed to make this connection. Therefore, only mean temperatures and standard deviations may be presented (see Table 9). Of the 28 buildings with participants completing S2, eight belonged to groups A and B, four to groups AC and C and 16 to group C only. In groups A and B, the mean temperature ranged from 20.93 °C to 22.79 °C, with standard deviations between 0.87 and 1.37. In buildings belonging to both groups AC and C, temperature data was missing for two buildings. For the remaining ones, the mean temperature ranged from 21.61 °C to 22.02 °C, with standard deviations between 0.99 and 1.46. Finally, in buildings belonging only to group C, the mean temperature ranged from 20.31 °C to 22.37 °C, with standard deviations between 0.46 and 3.31. Although it was not possible to obtain temperature measurements from the specific apartments of the participants, this summarised data shows small differences overall between the buildings belonging to different groups.

Mean temperatures during different parts of the day for all buildings were as follows: 21.56 °C for night, 21.48 °C for morning, 21.49 °C for afternoon and 21.55 °C for evening. This indicates a slightly lower temperature during mornings and afternoons than during evenings and nights. However, because this data represents the buildings in general and not specific participants' apartments, no test was conducted to analyse statistically significant differences.

In the buildings which had power control, mean temperatures one hour before and one hour after the load shifts did not differ by more than 0.31 °C. However, temperature variations in individual apartments were not investigated.

The World Health Organization recommends a minimum indoor temperature of 18 °C as *"a safe and well-balanced indoor temperature to protect the health of general populations during cold seasons"* (p. 34) but acknowledges that a higher minimum may be necessary for vulnerable groups [27]. According to the Public Health Agency of Sweden [28], recommended values for operating temperatures for indoor living spaces are typically 20–23 °C and 22–24 °C for vulnerable groups. Although the mean temperatures were within the standard recommended span, large variations were found between different apartments within the same building. In some cases, the measured minimum and maximum temperatures deviated from the recommended span.

Data on weather conditions during the trial was collected from Sweden's Meteorological and Hydrological Institute (SMHI) [29]. Air temperatures in the area during the trial (measured per hour) ranged from −1.1 °C to 10 °C, with an average of 6.5 °C and standard deviation of 2.3. Wind speeds in the area (measured as the maximum of the average wind speed and reported per hour) ranged from 1.1 to 8.9 m/s, with an average of 4.7 m/s and a standard deviation of 1.7. Correlations between indoor temperatures, outdoor temperatures and wind speed are presented for each of the buildings in Table 9. Although many statistically significant correlations were found, only a few of them were positive.

### 4.5. Analysis of diary entries divided by group

The total number of diary entries was 803 and the number of participants submitting diary entries was 48. The number of diary entries per person ranged from 1 to 47. The two groups that received notifications regarding load shifts, whether true or false, contributed a slightly higher average number of diary entries per person (18.8 for group A and 26.0 for AC compared with 14.6 for B and 13.7 for C). Furthermore, the participants who used the paper diary contributed, on average, almost

**Table 9**
Measured indoor temperatures for buildings with participants completing S2.

| Building | Participant group(s) | Mean temperature (°C) | Standard deviation | Mean temperature (°C) night (8PM–6 AM) | Mean temperature (°C) morning (6 AM–12 PM) | Mean temperature (°C) afternoon (12 pm–5 PM) | Mean temperature (°C) evening (5 PM–8 PM) | Correlation with outdoor temperature | Correlation with wind speed |
|---|---|---|---|---|---|---|---|---|---|
| 1 | A & B | 22.05 | 0.87 | 22.08 | 22.01 | 22.00 | 22.05 | 0.413** | −0.082 |
| 2 | A & B | 22.03 | 0.92 | 22.08 | 22.00 | 21.99 | 22.07 | 0.351** | 0.157** |
| 3 | A & B | 21.95 | 1.37 | 22.14 | 21.96 | 21.99 | 22.08 | −0.252** | −0.154** |
| 4 | A & B | 21.37 | 0.99 | 21.40 | 21.35 | 21.33 | 21.38 | −0.427** | −0.041 |
| 5 | A & B | 21.21 | 1.08 | 21.24 | 21.17 | 21.16 | 21.26 | 0.397** | −0.073 |
| 6 | A & B | 22.79 | 0.55 | 22.82 | 22.78 | 22.75 | 22.78 | −0.270** | −0.326** |
| 7 | A & B | 20.93 | 0.54 | 21.25 | 21.16 | 21.19 | 21.25 | −0.424** | −0.153** |
| 8 | A & B | 22.16 | 1.25 | 22.19 | 22.11 | 22.12 | 22.18 | −0.741** | −0.203** |
| 9 | C & AC | 22.02 | 0.99 | 21.88 | 21.80 | 21.81 | 21.87 | −0.602** | −0.281** |
| 10 | C & AC | 21.61 | 1.46 | 21.43 | 21.38 | 21.38 | 21.41 | 0.338** | 0.001 |
| 11 | C & AC | – | – | – | – | – | – | – | – |
| 12 | C & AC | – | – | – | – | – | – | – | – |
| 13 | C | 21.43 | 1.15 | 21.47 | 21.36 | 21.43 | 21.48 | −0.221** | −0.114* |
| 14 | C | 21.67 | 0.46 | 21.65 | 21.64 | 21.75 | 21.74 | 0.269** | 0.047 |
| 15 | C | 20.31 | 1.00 | 20:31 | 20.22 | 20.21 | 20.30 | −0.450** | −0.297** |
| 16 | C | 21.98 | 1.21 | 22.03 | 21.94 | 21.93 | 22.01 | 0.543** | −0.035 |
| 17 | C | 21.64 | 1.01 | 21.67 | 21.61 | 21.61 | 21.63 | 0.086 | −0.502** |
| 18 | C | 20.92 | 1.10 | 21.02 | 20.88 | 20.89 | 21.02 | −0.609** | −0.189** |
| 19 | C | 22.37 | 1.32 | 22.39 | 22.38 | 22.33 | 22.38 | 0.232** | −0.334** |
| 20 | C | 21.48 | 0.75 | 21.50 | 21.39 | 21.37 | 21.49 | −0.024 | −0.117* |
| 21 | C | 21.51 | 0.75 | 21.55 | 21.51 | 21.45 | 21.51 | 0.324** | −0.119* |
| 22 | C | 21.63 | 1.49 | 21.68 | 21.57 | 21.59 | 21.64 | −0.475** | −0.091 |
| 23 | C | 21.07 | 0.64 | 21.07 | 21.01 | 21.07 | 21.14 | −0.368** | −0.211** |
| 24 | C | 20.88 | 3.31 | 20.89 | 20.84 | 20.86 | 20.92 | 0.614** | 0.135* |
| 25 | C | 20.89 | 1.01 | 20.91 | 20.82 | 20.90 | 20.97 | 0.157** | 0.074 |
| 26 | C | 21.09 | 1.15 | 21.14 | 21.04 | 21.05 | 21.14 | −0.269** | −0.234** |
| 27 | C | 20.97 | 1.17 | 21.00 | 20.94 | 20.94 | 20.98 | −0.586** | −0.178** |
| 28 | C | 21.66 | 1.40 | 21.68 | 21.64 | 21.65 | 21.67 | −0.452** | −0.274** |

** $p < 0.01$, * $p < 0.05$.

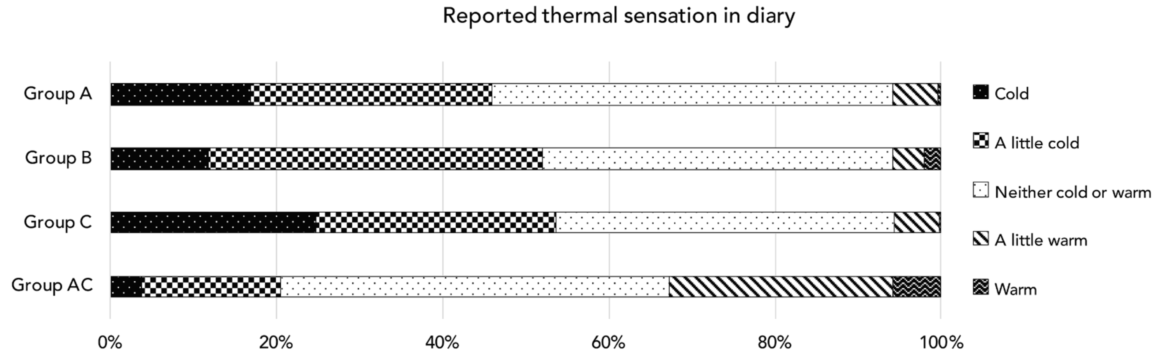


**Fig. 4.** Response distribution in diary entries, by group, on thermal sensation.

three times as many diary entries per person than those who used the digital diary (34.8 compared with 12.6).

The following figures show the response distribution of all diary entries regarding thermal sensation (Fig. 4) and thermal satisfaction (Fig. 5) in the four groups.

By assigning weights to the answer options regarding thermal sensation (from 1 to 5, with *cold* = 1 and *warm* = 5), groups A, B, C and AC had average scores of 2.43, 2.44, 2.28 and 3.14, respectively. A Mann-Whitney $U$ test was used to compare pairs of groups. This indicated that group AC experienced the temperature as statistically significantly warmer than all the other groups, while group C experienced it as statistically significantly colder than group A. However, when comparing the groups that had load shifts during the trial (groups A and B) with those without load shifts (groups C and AC), the test indicated no statistically significant difference in thermal sensation ($U = 72195$, $p = 0.061$).

Similarly, by assigning weights to the answer options on thermal satisfaction (from 1 to 5, with *very dissatisfied* = 1 and *very satisfied* = 5), groups A, B, C and AC had average scores of 3.02, 2.98, 2.75 and 3.24, respectively. A Mann-Whitney $U$ test indicated that group AC had a statistically significantly higher thermal satisfaction than the other groups, while group C had a statistically significantly lower thermal satisfaction than group A. When comparing groups A and B with groups C and AC, no statistically significant difference was found in thermal satisfaction ($U = 73867.5$, $p = 0.271$). However, these results were based on the total sample of diary entries and did not take account of the small number of participants in each group during the diary study, which ranged from six to 23 participants (see Table 5).

An analysis of the correlation between thermal sensation and thermal satisfaction from the total sample of diary entries showed a strong positive relationship, with $r = 0.632$ and $p = 0.000$. Group AC, whose members on average experienced the temperature as warmer than members of the other groups, also had the highest average score on thermal satisfaction, whereas group C had the lowest score on both thermal sensation and satisfaction.

A variety of comments were received, the majority complaining of negative experiences due to cold temperatures at home. One example was: *"Temperature in living room and kitchen is 20.4 °C. Way too low when you are 70 + years old"* (man, group C). Another reported: *"Still cold when we woke up, kitchen 20.7 °C and living room 20.9 °C, which feels cold"* (man, group C). Three participants from groups B and C specifically complained of a cold floor in the apartment and one participant from group C complained of bodily aches. Eight participants from groups A, B and C reflected on external influences on the indoor temperature, such as cold air leaking in from the windows or ventilation or the apartment warming up in sunny weather: *"When it's cloudy/rainy, it's usually a good temperature in the apartment. But as soon as the sun comes out it gets very hot"* (woman, group B). Three participants from groups B and AC commented that their apartments were generally warm even when their radiators are turned off:

> *Have had guests over today and the first comment you get is, "God, you've got it hot!". Everyone starts peeling off their sweaters and cardigans. I myself have probably adapted to it always being warm here at home. I haven't had the radiators on since I moved in almost 17 years ago. (Woman, group AC)*

Furthermore, all diary entries from groups A and B were analysed to compare whether there was any difference in thermal sensation and satisfaction between days with and without load shifts.[1] The average score on thermal sensation was 2.38 on days with load shifts and 2.47 on days without. The average score on thermal satisfaction was 2.99 on days with load shifts and 3.02 on days without. However, a Mann-Whitney $U$ test showed no statistically significant difference in either thermal sensation or satisfaction. A participant from group A reflected on one of the notifications he received regarding a load shift:

> *A lowering of the temperature for 3 h, from 1:00 to 4:00 AM, doesn't affect a well-insulated multi-residential building. Or, was it a test of a person's subjective experience of having received information about a temperature decrease that in reality would not affect the air temperature? "Fake news"? :) (Man, group A)*

A few comments also described actions taken to improve comfort, such as wearing extra clothes, using a blanket, or drawing the curtains to prevent the heat from leaking out through the windows. One participant reported: *"Since I'm frozen, I wear double socks. The outermost pair are thermal socks. I also have a large dog who generates heat next to me which, I think, makes me feel warm enough at the moment"* (woman, group C). Another explained that *"if it's cold, I just want to nestle and become inactive"* (woman, group A). Four participants from groups C and AC commented that they had opened the windows or the balcony door, either because they found the air thick or the temperature too warm: *"We need to keep the window open, otherwise it will be stuffy, but it makes it cold in here"* (woman, group C). Another commented (nighttime): *"Opened windows in the bedroom, closed radiators, cold outside but still it feels warm indoors (22.4 [°C] according to the thermometer)"* (woman, group AC).

### 4.6. Analysis of diary entries divided by time of day

To analyse whether there was a difference in thermal sensation and satisfaction depending on the time of day, the diary entries were again analysed using a Mann-Whitney $U$ test, but with time of day as the grouping variable. The response distribution regarding thermal sensation is shown in Fig. 6 and thermal satisfaction in Fig. 7.

Regarding thermal sensation, the average score was: for *night* 2.50, *morning* 2.43, *afternoon* 2.58 and *evening* 2.57. Similar to the result from

[1] Although the number of load shifts varied between the buildings, all diary entries from groups A and B on days with load shifts in at least one of the buildings were included in *days with load shifts* in this analysis.

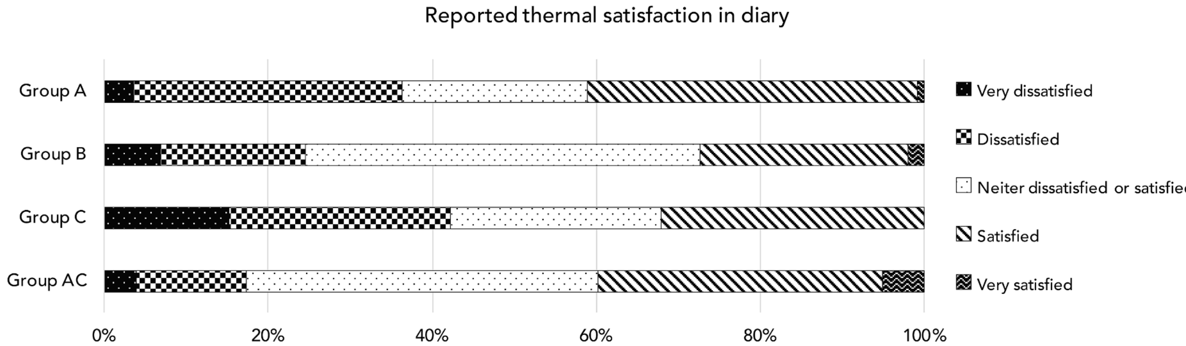


**Fig. 5.** Response distribution in diary entries, by group, on thermal satisfaction.

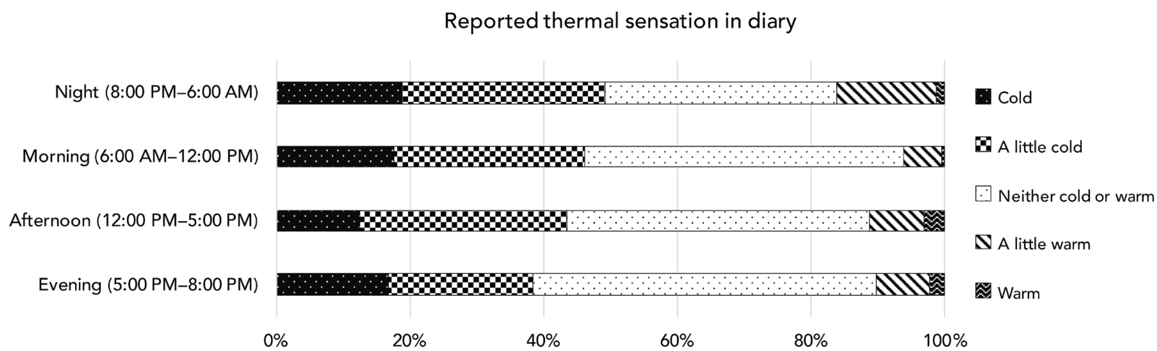


**Fig. 6.** Response distribution in diary entries on thermal sensation, by time of day.

S1, this indicated that the temperature was generally experienced as being slightly colder during mornings. However, the Mann-Whitney *U* test showed no statistically significant difference in thermal sensation between any of the four timespans of the day, with $p > 0.05$ in all combinations.

Regarding thermal satisfaction, the average score was: for *night* 2.83, *morning* 2.98, *afternoon* 2.98 and *evening* 3.04. The Mann-Whitney *U* test showed that there was a statistically significant difference in thermal satisfaction only between *night* and *evening* (U = 17011.5, $p = 0.035$), whereas the other combinations all had a *p* value greater than 0.05.

Two participants from groups B and C complained about cold mornings: "*Felt freezing cold in the apartment when I got up this morning*" (woman, group C). Two other participants in group A and C explained that they preferred slightly colder temperatures overnight: "*Although it gets colder, I want the heating to be turned off at night*" (woman, group C). One participant experienced a lack of ventilation, particularly during evenings: "*Finding that that the air becomes heavy towards evening*" (woman, group AC).

### *4.7. Analysis of diary entries divided by gender*

In a final comparison of the diary entries, a Mann-Whitney *U* test was conducted, with gender as the grouping variable. On thermal sensation, the male participants got an average score of 2.46, compared to 2.55 for the female participants. This indicates that, on average, women in this study experienced the temperature as slightly warmer than men. Yet, the Mann-Whitney *U* test showed no statistically significant difference in thermal sensation between the genders.

On thermal satisfaction, the male participants got an average score of 3.04, compared to 2.89 for the female participants. The Mann-Whitney *U* test confirmed that men were statistically significantly more satisfied with the indoor temperature during the trial than women (U = 70454, $p = 0.032$).

### *4.8. Thermal perception at home after the trial*

Table 10 presents the response averages to questions from S2 for the different participant groups and for men and women. The responses were analysed in a Mann-Whitney *U* test comparing (1) the individual groups, (2) groups A and B with C and AC and (3) men and women. The largest difference between the combined groups (A + B and C + AC) was found in responses to the last question in Table 10, regarding the experience of sudden temperature changes. This result suggests that the groups with load shifting noticed sudden temperature changes in their apartments to a greater extent than those without. The same question also showed the greatest difference in responses from men and women, indicating that male participants experienced sudden temperature changes in their apartments to a greater extent than female participants. However, the analysis showed no statistically significant difference in any of the comparisons, with $p > 0.05$ in all cases.

Regarding thermal sensation during different parts of the day, the averages turned out to be 2.15 for *morning*, 2.48 for *daytime*, 2.18 for *evening* and 2.40 for *night* in S2. A Wilcoxon signed-rank test showed that both mornings and evenings were perceived as statistically significantly colder than daytime and night. In S2, 65% (n = 47) experienced the temperature as either *too cold* or *a little too cold* during mornings. 68% (n = 49) experienced the temperature as either *too cold* or *a little too cold* during evenings. Two participants from group A commented that they could accept a lower temperature during the night as long as the mornings (and evenings) were warmer. They explained as follows:

> *On some nights, I've felt that you've raised or lowered the heat. Then I've added an extra blanket or removed one. It's ok that it's colder during the night, if I know in advance. Of course, it's nice to have it a little warmer during morning and evening. (Woman, group A)*
>
> *The night temperature could be lowered slightly compared to mornings. None of the controls on the old radiators can be regulated (nothing happens, I think it is always fully open. Many people used to air out for long periods, even in the middle of winter). (Man, group A)*

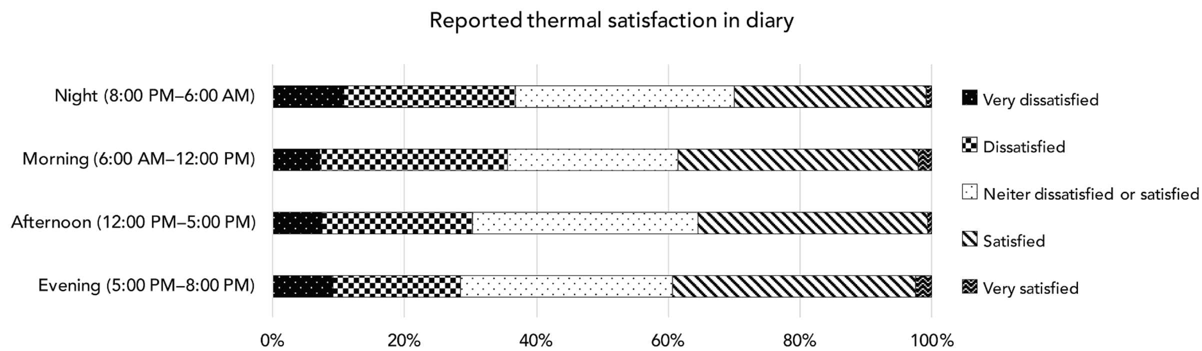


**Fig. 7.** Response distribution in diary entries on thermal satisfaction, by time of day.

Another participant from group A commented that it had been especially cold during the nights. Five participants from groups B and C commented that it had generally been too cold in their apartments. One respondent made the following criticism:

*I care very much about the environment and save electricity in every way I can, but it doesn't feel worth freezing every day throughout the winter. I think the landlord wants to save money and that has nothing to do with the environment at all. (Woman, group C)*

A frequent topic mentioned was the lack of control over the temperature in the apartment. Four respondents from groups A, B and C commented that their radiators were always set to the maximum level but that this, nevertheless, failed to provide enough heat. Two participants explained:

*Our heaters are at the maximum position all the time, but they are barely warm most of the time. The only time we actually experienced warmth was during the period when it got closer to zero degrees and was snowing. (Woman, group C)*

*It's hardly been possible to answer the questions because the apartment is unusual, with large glass walls and radiators that are too small. Also, the radiators cannot be adjusted to a higher temperature. They're already set to max but don't get especially hot. The temperature in the apartment already varies between 17 and 35 °C depending on the season and external influences from weather and wind. (Man, group A)*

The average scores for the reported thermal sensation in different rooms were 2.55 for the bedroom, 2.12 for the living room, 2.54 for the kitchen and 2.64 for the bathroom. A Wilcoxon signed-rank test showed that the living room was perceived as statistically significantly colder than all other rooms, in line with the results from S1. The other comparisons did not indicate any statistically significant differences, with $p > 0.05$.

The respondents to S2 were also asked what they had done if they felt too cold or too warm at home during the two trial weeks. The response distribution is shown in Figs. 8 and 9. Overall, it was more common to take action due to feeling cold than feeling warm. Nevertheless, 33% (n = 24) answered that they had opened a window when feeling too warm during the trial. Common actions when feeling cold that required energy were to drink or eat something warm (35%, n = 25) and to take a hot shower or bath (24%, n = 17). Thirteen percent (n = 9) answered that they had turned on an extra fan heater. The rather low number that regulated the temperature on their radiators or floor heating may be partly attributed to a lack of opportunity to do so because sometimes the radiators were pre-set to the maximum or minimum level.

Finally, two participants from groups A and C commented that it had been interesting to be part of the study. One of them explained:

*I think it's been good for me and my partner to actually reflect on how we feel in the apartment. We've often said that we're freezing and that it's cold in the apartment, but now, since November at least, the radiators have been running and [the apartment has] warmed up a bit. We also leave the oven open after we have used it so that the heat comes out into the apartment. (Woman, group C)*

## 5. Discussion

This section discusses thermal perception in relation to building properties, demographics and different times of the day. It then discusses the role of communicating about load shifting, attitudes towards heating and energy use at home and individual preferences and control. The section ends with a discussion of the study methodology and participant groups.

### 5.1. Thermal perception and building properties

The analysis of thermal perception at home during and after the trial indicated that, with some exceptions, the participants of this study generally experienced the temperature to be more towards the cold end of the scale. Still, average indoor temperatures at the building level were within the range recommended by the Public Health Agency of Sweden [28], albeit with major variations between individual apartments.

In S1, a majority experienced being too cold at home during the winter, at least a few times per week. Several participants explained that the temperature in their apartments varied greatly between different seasons. Regarding thermal satisfaction, the results from both surveys and the diary showed major variation among participants. However, the strong positive correlation between thermal sensation and thermal satisfaction in the total sample of diary entries confirmed that, during this trial, more participants were dissatisfied due to experiencing the

**Table 10**
Questions and response averages in S2. For response options, see Table 7.

| Question | A | B | C | AC | A + B | C + AC | Women | Men |
|---|---|---|---|---|---|---|---|---|
| How satisfied have you been with the temperature in your home during the last two weeks? | 2.93 | 2.93 | 2.75 | 3.20 | 2.93 | 2.86 | 2.90 | 2.87 |
| Did you, during the last two weeks, experience the temperature in your home as warmer or colder than usual? | 2.53 | 2.50 | 2.73 | 2.90 | 2.52 | 2.78 | 2.76 | 2.54 |
| Did you, during the last two weeks, experience the temperature in your home as better or worse than usual? | 2.73 | 2.71 | 2.84 | 2.70 | 2.72 | 2.80 | 2.86 | 2.64 |
| How often, during the last two weeks, did you experience any sudden temperature changes in your apartment? | 2.29 | 2.38 | 1.97 | 2.22 | 2.33 | 2.03 | 2.00 | 2.36 |

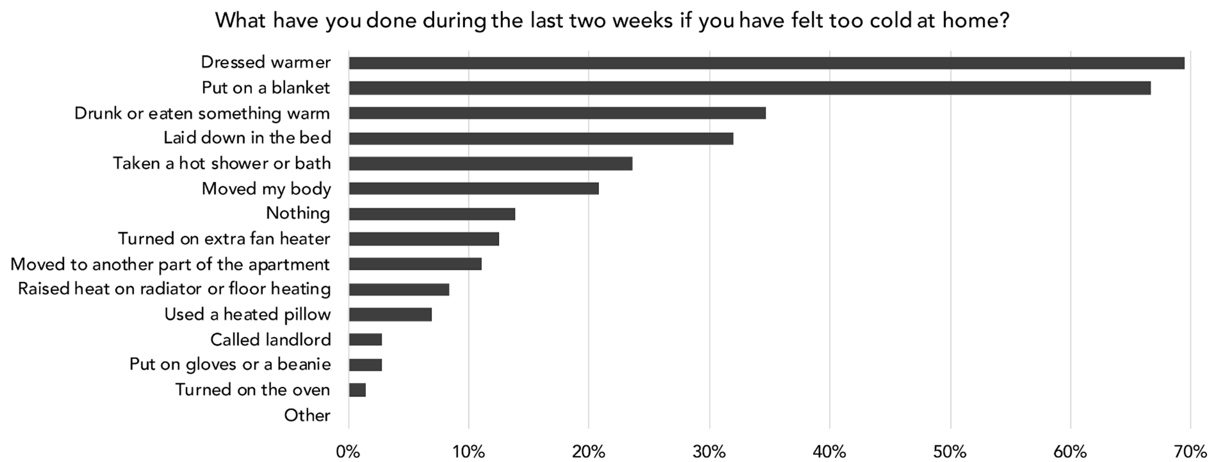


**Fig. 8.** Response distribution in S1 regarding actions carried out when feeling too cold at home.

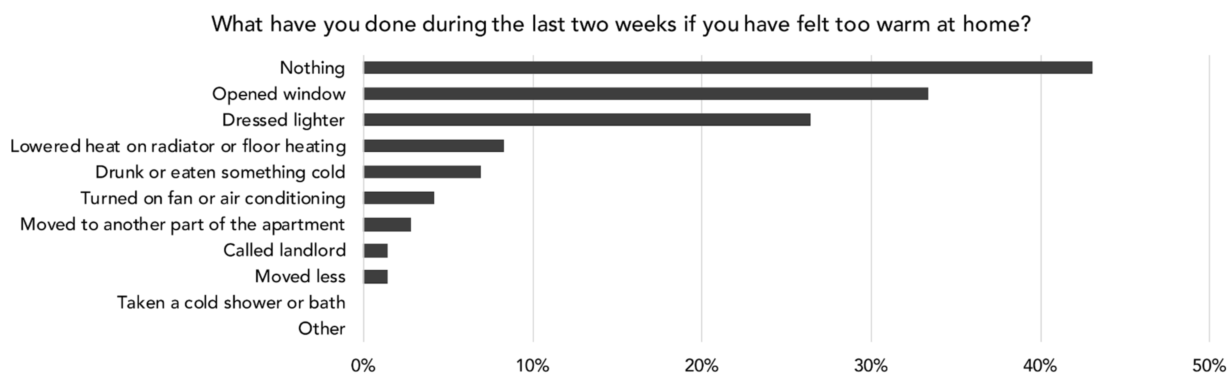


**Fig. 9.** Response distribution in S1 regarding actions carried out when feeling too warm at home.

temperature as cold than warm. Because the trial was conducted during early winter, this result is not surprising.

In many cases, the participants' comments indicated that the indoor temperature was greatly affected by outdoor conditions such as wind, temperature and sun exposure. Additionally, the buildings included in the study exhibited major variations in the energy performance and indoor temperatures of different apartments. Thus, building characteristics and the location of the apartments in a building play an important role in the residents' perception of the indoor temperature. However, the energy consumption of buildings is also affected by residents' behaviour and heat-related practices.

### 5.2. Thermal perception and participant demographics

The division between male and female participants in this study was largely even, with a slight majority of female participants. In contrast to previous research, for instance [20], no statistically significant difference in thermal sensation was found between men and women in this study. Still, the analysis of diary entries showed a statistically significant difference in thermal satisfaction, with male participants on average being more satisfied with their indoor temperature. However, neither of the surveys confirmed this as their results on thermal satisfaction pointed in the opposite direction but without statistically significant differences. Therefore, no conclusions may be drawn from this study regarding differences in thermal perception between men and women.

The participants of the study reported a varying number of days normally spent at home per week during daytime. This may result in different preferences regarding indoor climate conditions, with thermal comfort more highly valued by those who spend more time at home. Further research is needed into how thermal perception during load shifting relates to gender and other demographic characteristics such as age, cultural background and time spent at home. This will provide a better understanding of how load shifts are experienced by different groups in society.

### 5.3. Thermal perception at different times of the day

Both survey results and the diary results indicated that indoor temperature was, in general, experienced as slightly colder during mornings than at other times of the day. S1 exhibited a statistically significant difference in thermal sensation between morning and all other parts of the day. S2 showed that both mornings and evenings were perceived as statistically significantly colder than daytime and night. In the diary results, the differences were not statistically significant. Although mornings had the lowest mean indoor temperature overall, it was not possible to analyse statistically significant differences in temperature between different times of the day in specific participants' apartments. Because demand-side management is often focused on achieving peak shavings during mornings, it may be challenging to prevent significant temperature reductions and negative effects on residents' thermal comfort during this time of the day. Peak shavings during mornings may also be further complicated by practices such as having the windows open overnight, which was previously highlighted as a challenge by Larsen and Johra [10]. In the present study, 33% of respondents in S2 stated they had opened a window during the trial when feeling too warm and a few comments also indicated that this practice was carried out due to poor ventilation.

### 5.4. Communication about load shifting

As indicated in one of the survey comments and previously highlighted by Sweetnam et al. [9], communication about how the heating system is controlled might potentially increase acceptance of load shifting because it would enable residents to be more prepared for, and understand the benefits of, upcoming load shifts. It might be beneficial if information about scheduled load shifts was provided to help households adapt some of their heat-related practices to minimise heat waste; Royston [30] refers to this as "heat-out-of-place" and "heat-out-of-time". An example of such a practice is opening windows to let warm air escape the home in the winter, especially in connection to load shifts. However, information alone does not necessarily lead to changed behaviour [31]. How best to communicate load shifting to support acceptance and prevent further temperature deviations due to heat-related practices at home therefore requires further investigation. Additionally, further insights are needed into when and why different heat-related practices take place at home.

### 5.5. Attitudes towards heating and energy use at home

A majority of the survey respondents found it important to save energy to reduce their environmental impact and in both S1 and S2, respondents reported that they tried actively to reduce their daily energy consumption. Saving energy to minimise costs was generally perceived as less important, which is not surprising because heating was included in the rent. Tenants may also have different expectations regarding the indoor temperature than homeowners. Interestingly, the comparison of results from S1 and S2 showed that, after the trial, significantly fewer participants could imagine allowing a greater temperature variation in their apartments to save energy than before it. These results were based on quantitative data collected in the form of agreement with a statement and, thus, we cannot explain the reasons why acceptance dropped throughout the study. To gain deeper insight it is therefore advisable, for future studies of households' acceptance of demand-side management, to combine large-scale quantitative data collection with qualitative methods. However, if thermal satisfaction is already low, it is understandable that there would be resistance to making further compromises on thermal comfort.

### 5.6. Individual preferences and control

The responses to another statement indicated that the participants generally felt they lacked control over the heating in their apartments and this was confirmed by several comments. This is in line with previous research by Henning [21] and Renström and Rahe [22]. In the present study, a positive correlation was found between the statements concerning control and acceptance of temperature variations. This indicates that those who experienced having better control of their heating could, to a greater extent, imagine allowing larger temperature variations at home.

Furthermore, comments showed that preferences regarding indoor temperature varied. For instance, some participants preferred colder night temperatures, whereas others had negative experiences of overnight temperatures being too low. The findings also indicated that the living room was generally perceived as colder than other rooms in the apartment. This suggests that greater individual control of temperature, at both apartment and room level, might engender greater satisfaction with the indoor temperature while potentially also minimising heat losses. As previously suggested by Madsen and Gram-Hanssen [32], heat losses from airing the bedroom overnight might be avoided by having more capacity to use different temperature zonings in the apartment. However, Larsen and Johra [10] found that, overall, the introduction of increased control over the indoor temperature through smart technology contributed to higher indoor temperature setpoints and greater requirements for indoor comfort. Additionally, they found that their study participants preferred heating flexibility to be controlled centrally or through machine learning. For future studies, it would therefore be interesting to explore whether and how individual preferences might be better met through centrally controlled load shifts. One option would be to keep the load shifts centrally controlled while allowing for greater control over the indoor temperature during the remaining time when there are no shifts. Alternatively, in addition to simply informing tenants of upcoming load shifts, residents might be offered the possibility of rejecting such shifts if they already experienced the temperature as being too low or too high. Although this might be beneficial in protecting vulnerable groups, it may undermine the demand-side management strategy if too many residents were to exercise an option to reject load shifts. From a technical perspective, it might also prove too complicated to exclude some apartments, as load shifts and indoor temperature settings are currently managed at building level. Another opportunity would be to explore alternative ways of achieving thermal comfort. Previous research has highlighted person-heating as a less resource-intensive, more direct way of improving thermal comfort compared to keeping a high indoor temperature; by using heating pads or hot water bottles, for example [33,34].

### 5.7. Methodology and participant groups

In groups A and B, where load shifts were applied during the trial, the diary study results showed no statistically significant difference in thermal sensation or satisfaction between days with and without load shifts. However, because the number of participants in the diary study was low, the results cannot be used to conclude that no differences were experienced or that acceptance of load shifts was high.

Group AC, members of which lived in buildings without load shifting but who still received false notifications about planned load shifts, rated their thermal sensation on average more towards the warm end of the scale than did members of the other groups in both the diary study and S2. However, this difference was only statistically significant in the analysis of the diary entries. Because this was based on the number of entries rather than the number of participants, which was low, it is not possible to draw conclusions regarding actual differences between the groups. There were also differences in the number of diary entries per person, with a higher average for participants who used the paper diary and for participants of groups A and AC (the two groups that received notifications about load shifts). This might have skewed the results. Furthermore, the actual indoor temperature measurements could only be compared at the building level and not between participants' specific apartments.

The diary method allowed the authors to collect data in real time regarding participants' thermal sensation and satisfaction. This enabled comparison of each diary entry with the conditions at that specific time, such as the occurrence of load shifts. However, a challenge of this methodology which requires further consideration is how to ensure that all participants are equally represented when some contribute more diary entries than others.

To collect more insights regarding the perception of indoor temperature and load shifts, this study may be repeated on a larger scale. The heat power control schedule should be further developed into a more representative schedule to achieve peak-hour demand reductions. Ideally, indoor temperature data should be collected at the apartment level to enable an analysis of how much the temperature is actually affected by load shifts. Additionally, more qualitative data should be collected in the form of interviews to complement the mainly quantitative data collected in the surveys and diary entries.

## 6. Conclusion

This study evaluated the perception of indoor temperature conditions and demand-side management from the perspective of households living in multi-residential buildings in the south of Sweden. Half of the participant groups were irregularly exposed to load shifts in a two-week trial conducted during early winter. Between the days with and without load shifts, no statistically significant difference was found in thermal sensation or thermal satisfaction. However, significantly fewer participants could imagine allowing more variation in temperature at home to save energy after the trial than before. Due to a relatively low number of participants taking part in the study, it is not possible to draw conclusions regarding differences in thermal perception between the participant groups.

The study highlights several factors that may influence the perception and acceptance of demand-side management in residential space heating. These include: (1) set indoor climate conditions, (2) timing and magnitude of the load shifts, (3) individual control and (4) communication.

Firstly, building-related problems which cause negative experiences of the indoor climate, such as poor insulation or insufficient ventilation, should be resolved in order to support overall satisfaction with the indoor climate.

Secondly, major temperature reductions during times perceived as particularly cold and major temperature increases during times perceived as particularly warm should both be avoided. In this study, mornings were perceived as colder than other times of the day. For future studies, further insights are needed regarding how residents perceive the temperature at different times of the day, when and how heat-related practices take place and what implications these have for the design of demand-side management strategies.

Thirdly, the results indicated a demand for more control over the indoor temperature as well as a positive correlation between perceived control and willingness to accept larger temperature variations. Thus, another topic for future studies is to explore how greater flexibility in heating demand might be combined with greater experience of control over the indoor climate to increase residents' thermal satisfaction whilst saving energy.

Finally, in accordance with previous research [9], the authors suggest that communication about upcoming load shifts may play an important role in promoting acceptance of demand-side management and ensuring a well-functioning heating system. However, more research is needed into how best to manage such communication.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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