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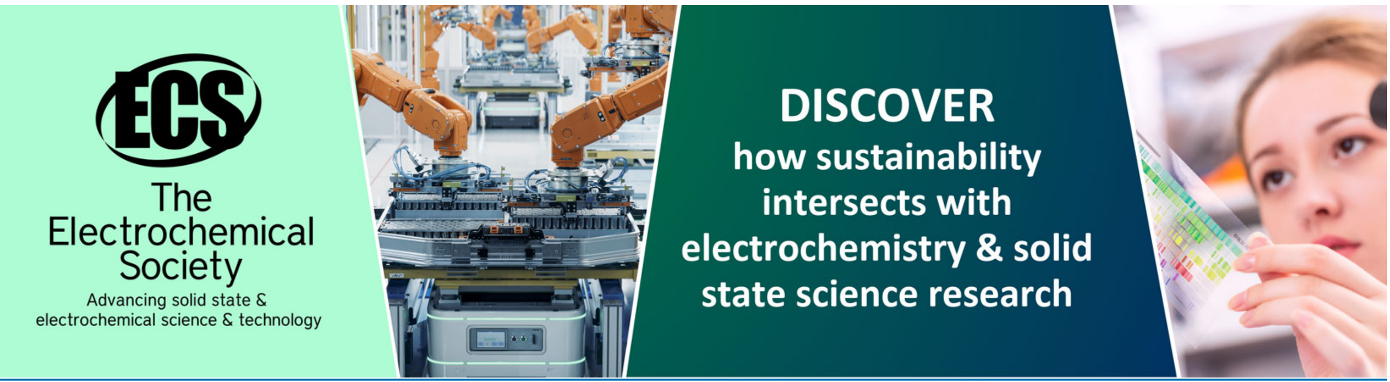

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On the temporal dimension of adaptive thermal comfort mechanisms in residential buildings

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Abstract. In response to the change of indoor thermal environment, building occupants constantly interact with the surrounding environment through various adaptive behaviours. The purpose of this study is to better understand the adaptive thermal comfort mechanisms by investigating the interrelationship between the expectation of the occupants (the psychological adaption), their behavioural adjustment (the physical adaption), and the indoor thermal environment in the context of residential buildings. Eleven households in South Korea participated in this longitudinal field study carried out between 2015 and 2017. The indoor thermal environmental parameters, the occupant subjective evaluations of thermal comfort, and their adaptive behaviour pattern were monitored. On average, 1,512 datasets from each household and a total of 16,632 datasets were collected and analyzed. Our analysis focused on understanding both the temporal dimension (i.e. duration of thermal discomfort episodes) and the intensity of stimuli (i.e. deviation from the comfort zone) both before- and after the participants' decision on the use of air-conditioners. The study proposes the constructs of 'discomfort capacity' and 'comfort restoration' as multi-dimensional indices to better understand the triggering mechanisms for household air-conditioner usage. Using these indices, the study quantified householders' tolerance of thermal discomfort events before they resort to air-conditioning.

1. Introduction

1.1. Background

It is possible to find conditions under which most individuals will have a positive sensation in relation to thermal comfort [1]. One such approach is "adaptive thermal comfort", which integrates the subject's thermal preferences in deciding the thermal environment, where each subject will experience optimum comfort for most of the time they spend in the environment [2,3]. The thermal adaptation can be influenced by the duration and indoor/outdoor climatic conditions to which one has been exposed to [4,5,6,7]. In adaptive comfort theory, if a change occurs such as to cause discomfort, people react in ways to restore their comfort [8]. The physical adaptive behaviours (i.e., behavioural adjustment) that typically occur inside a building include turning on/off heating/cooling equipment, adjusting thermostat settings, changing clothing, opening/closing windows or doors, drinking beverages, turning on fans, etc. The triggers for adaptive behaviours are considered to be different in different building typologies. Compared to their office workplace counterparts, occupants in their own home typically have a much wider palette of adaptive comfort opportunities to select from, such as turning on/off air-conditioner, opening/closing windows and/or doors for comfort ventilation, or increasing or decreasing their clothing insulation across a wider range, compared to office workers [9,10].

Among various adaptive behaviours that can occur in residential buildings, the operation of the air-conditioner is of a key interest in this study. The accelerating penetration rate into the residential sector can be attributed to demand in space cooling in summer. Householders' air-conditioner operation

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patterns, therefore, have significant implications for energy consumption and peak electricity demand in the residential sector [11,12].

According to the previous study conducted in a continental climate in China [13], the average indoor temperature that triggers householders' use of air-conditioner in summer was 27.6°C, resulting in a cooling of the room by 4.2°C on average during the average period of operation lasting 3.7 hours. A more moderate pattern of air-conditioner usage was observed in a subtropical coastal climate in Australia [14]. In the Australian study, the mean cooling trigger temperature was 27.9°C (SD 2.0°C), and the mean cooling stop temperature was 25.2°C (SD 1.8°C). The indoor air temperature change between the trigger and stop was approximately 2.6°C, with the mean operation duration of 2.5 hours. A similar study in South Korea [15] reported that, the mean air temperature at which air-conditioner switch-on behaviour was triggered was 26.5°C (SD 1.5°C) in summer. The operation of air-conditioners began at a mean indoor air temperature of 30°C, and the operation stopped at the indoor air temperature of 26.9°C [16]. In this study, we examined the time period during which an occupant endured thermal discomfort as a key triggering factor for adaptive behavioural actions. Previous studies looked into the time period of thermal adaptation over a relatively long-term (i.e., 4.25 days at the shortest, and 48 days at the longest), despite thermal adaptation occurring at different time-scales ranging from minutes, hours, days, up to years [5,17,18,19,20,21,22,23].

Research on the behavioural contexts of air-conditioning have been conducted previously; however, no clear findings was obtained regarding factors (e.g., sudden change in indoor air temperature and increasing discomfort of occupant) that induce and maintain the adaptive behaviour. As such, research findings are unclear regarding the temporal domain of adaptation within a short time-frame that should be directly reflected in the cooling strategy. The underlying premises and the processes of adaptive behaviour (e.g., behaviour-indoor/personal thermal environment parameter-human body heat balance-thermal comfort) still need rethinking.

1.2. Study objectives
In this study, we seek to understand the underlying causal mechanism of adaptive comfort behaviour (i.e., operation of air-conditioners) by taking into account multiple dimensions including the duration and the stimulus intensity in discomfort episodes. We employed the combined intensity and duration metrics of degree-day and degree-hour in our research method. Multi-dimensional data (e.g., subjective thermal comfort responses, time, and indoor temperature variations) were linked with the occurrence of air-conditioner operations (i.e., switch on/off) in the sample households. The main aim of this work is to better understand discomfort tolerance of householders – i.e., how much time and how intense stimulus are needed before prompting the decision to resort to the air-conditioner. The study results are thought to facilitate the understanding of realistic behaviour patterns of householders with regard to the operation of air-conditioners.

2. Methods
2.1. Experimental process
The experimental data for this study were measured in the Korean summer (June, July, and August) of 2015, 2016, and 2017. A realistic representation of the residential environment is crucial for the valid evaluation of occupant comfort and associated behaviours. Hence, the apartment in which the occupant actually resides was selected as the field laboratory in this experiment. Eleven households in apartment buildings participated in field experiments. The surveyed apartment buildings were evenly distributed throughout Daegu, South Korea and consisted of various numbers of households, household area, numbers of floors, and heat sources; therefore, these apartment buildings were considered to comprehensively reflect the general characteristics of apartment buildings in Daegu.

The experimental data were collected during which time most of the daily living activities are executed (i.e., 12 hours from 08:00 to 20:00). The operation of the air-conditioner was decided as per the occupants' will. The air-conditioner of each household was set to 26°C. In South Korea, the lower limit of cooling setpoint temperature of 26°C is universally applied for nearly all kind of buildings [24]. The energy recovery ventilation (ERV) system was controlled to satisfy the minimum ventilation requirement for apartment buildings (0.7 times per hour) [25].

In order to secure the reliability of the measurement results, the measurement methods (physical measurements) used were those indicated in the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) Standard 55 'Thermal Environmental Conditions for Human Occupancy' for the evaluation of comfort in existing buildings [26]. Data were measured at the centre of experimental space, at a distance 1m and 3m from the outlet of the air-conditioner, and under the outlet of the ERV system. The measuring instruments were placed 1.1m above ground level (head-height when seated). The personal parameters were recommended as 0.5clo (the summer season typical clothing type) and sedentary activity as indicated in the ASHRAE standard 55 [26].

The occupants were questioned about their respective thermal comfort status every 5minutes (evaluated through a seven-point scale). The following values for the thermal comfort sensation were considered: -3 for "very uncomfortable"; -2 for "uncomfortable"; -1 for "slightly uncomfortable"; zero for "neutral"; +1 for "slightly comfortable"; +2 for "comfortable"; +3 for "very comfortable" [26]. Occupants' adaptive behaviour was recorded whenever they occurred based on the classic "right-here-right-now" method. Among the various adaptive behaviours, we focused on the behavioural adjustment of operating the air-conditioner to improve indoor thermal environment. We collected the behavioural adjustment patterns of "before-and-after occurrence of adaptive behaviour" in units of cycles. Using this process, 1,512 datasets were collected, on average, from each of the eleven households, resulting in a total of 16,632 datasets.

2.2. Experimental concept design

We analysed the temporal dimension in the short-term (i.e., minutes before- and after adaptive behaviour) to identify the response of the adaptive thermal comfort mechanisms. Indoor air temperature generally increases until the adaptive behaviour is occurred, and decreases once adaptive behaviour occurs. To more closely observe the entire timespan of this behavioural adjustment process, we derived 'Discomfort capacity' and 'Comfort restoration'.

'Discomfort capacity' and 'comfort restoration' are based on the concept of cooling degree hour (CDH), which determines the cooling demand from the sum of temperature exceedances above a cooling base temperature (i.e., 26°C [24]). For a case in point, the concept of degree-day (or degree-hour) is recommended in "Long-term evaluation of the general thermal comfort conditions: Method B. Degree hours criteria" section of the European Standard EN 15251 [27] for the evaluation of the thermal comfort conditions over a certain period of time (season, year) using weighted actual operative temperature deviations beyond an acceptable range during hours of occupancy and the duration of deviation as variables.

'Discomfort capacity' in this study is defined as the thermal tolerance of an occupant from when the occupant expresses thermal discomfort for the first time (i.e., CSV<0) until the moment when the occupant performs an adaptive comfort behaviour (in this case switch-on of the air-conditioner). It is calculated as the cumulative value of a difference between the measured indoor air temperature and the cooling base temperature per minute during δT_d (i.e., the timespan from which the occupant declared discomfort to the occurrence of adaptive behaviour). 'Comfort restoration' is in this study refers to the attainment of thermal comfort by an occupant in response to the adaptive action (i.e., air-conditioner switch-on) till the occupant has removed thermal discomfort (i.e., CSV≥0). It is quantified here as the cumulative indoor air temperature deviation from the cooling base temperature since the occurrence of the adaptive behaviour (i.e., air-conditioner switch-on) until the time the occupant's thermal comfort vote reaches neutral (i.e., CSV = 0) (δT_c). We then derived the comfort base temperature corresponding to the neutral sensation (CSV=0).

A conceptual diagram in Figure 1 shows the change in indoor air temperature before- and after adaptive behaviour (the operation of the air-conditioner), which is illustrated as the sum of these two discomfort periods or the entire time the occupant felt discomfort (δT).

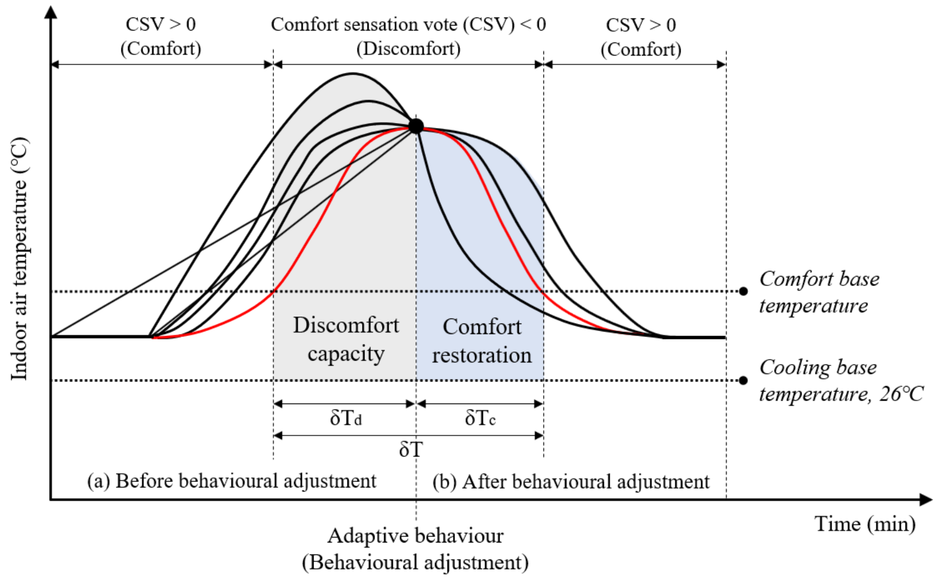

Figure 1. Conceptual diagram of 'discomfort capacity' and 'comfort restoration'.

3. Results and discussion

The observed indoor air temperature was 27.2°C (SD 1.6°C) on average, which was slightly higher than the initial setting temperature (26°C). Table 1 summarized the amount of clothing, metabolic rate and other background information. The average clothing amount of the participants during the experiment was between 0.48 and 0.51clo. The average metabolic rate was between 1.0 and 1.2met.

Table 1. Clothing insulation, metabolic rate, and background information (Mean±Standard deviation).

Gender	N	Age	Height (cm)	Weight (kg)	Clothing insulation	Metabolic rate
Male	24	39.32±14.01	175.04±4.55	72.72±8.76	0.48±0.02	1.2±0.2
Female	29	35.96±12.52	161.96±4.96	57.37±6.18	0.51±0.03	1.0±0.1
Total	53	37.49±13.21	167.91±8.11	64.35±10.71	0.49±0.03	1.2±0.2

Equations 1 and 2 were used to calculate 'discomfort capacity' and 'comfort restoration', respectively.

$$Discomfort\ capacity(℃ \cdot min) = \sum_{n=0}^{i}(T_x - Cooling\ base\ temperature) \quad (1)$$

$$Comfort\ restoration(℃ \cdot min) = \sum_{n=0}^{j}(T_x - Cooling\ base\ temperature) \quad (2)$$

$$T_x \begin{cases} Apply\ Eq\ (1), (2)\ when\ T_x \geq Cooling\ base\ temperature \\ 0, otherwise \end{cases}$$

where i is the number of minutes for which before of adaptive behaviour occurrence (δT_d), j is the number of minutes for which after of adaptive behaviour occurrence (δT_c), and cooling base temperature is 26°C. Table 2 shows the discomfort capacity and the comfort restoration calculated for each household.

Table 2. Discomfort capacity and comfort restoration calculated for each household.

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	Total	Mean (SD)
Comfort base temperature (°C)	27.6	27.4	27.1	27.2	27.6	27.7	27.2	27.2	27.9	27.3	27.8	-	27.4 (0.3)
δT (min)	22.7	24.4	30.4	29.9	25.0	23.5	23.3	23.5	23.2	23.7	23.2	-	24.8 (2.6)
δT_d (min)	17.2	18.1	15.5	15.8	18.3	16.0	17.4	16.7	17.6	17.4	17.2	-	17.1 (0.8)
δT_c (min)	5.5	6.3	4.9	4.1	6.7	7.5	5.9	6.8	5.6	6.3	6.0	-	5.9 (0.9)
Discomfort capacity (°C·min)	42.6	54.2	24.9	30.5	53.1	49.0	36.1	30.1	55.5	42.8	49.0	468.1	42.5 (10.2)
Comfort restoration (°C·min)	9.8	12.6	5.1	6.2	11.6	13.5	7.8	8.9	11.6	10.1	13.1	110.1	10.1 (2.7)

-Note: SD: Standard deviation.

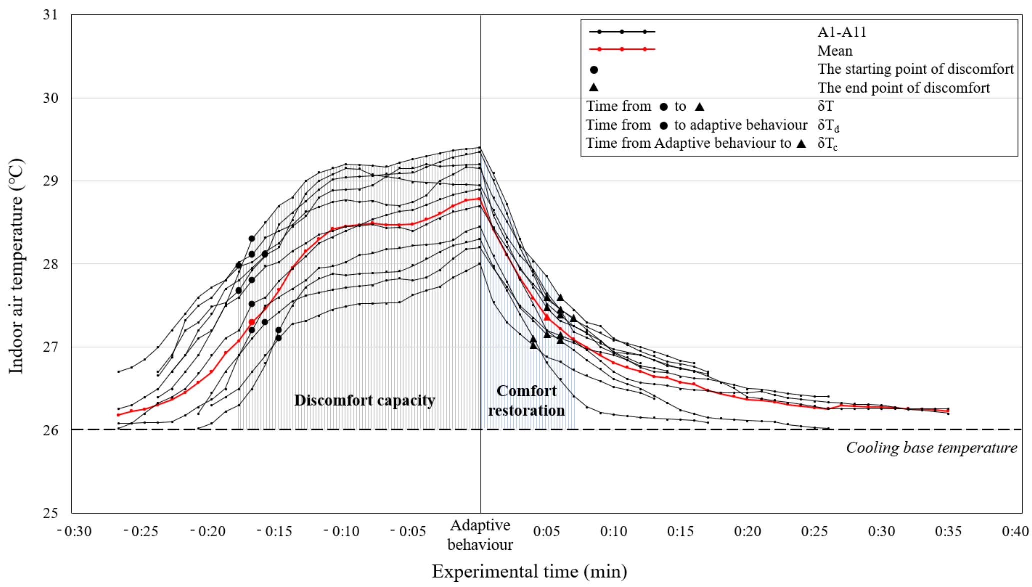

Figure 2. Discomfort capacity and comfort restoration in relation to before-and-after the occurrence of an adaptive behaviour.

In accordance with the occurrence of adaptive behaviour, Figure 2 presented the schematic of the discomfort capacity and the comfort restoration. The measured indoor air temperature for each household shows a large deviation before adaptive behaviour but converges to a certain level (i.e., 26°C) due to the effect of the air-conditioner operation. The average operation time when adaptive behaviour occurred (the operation of the air-conditioner) was 20.7 minutes with a deviation of 8.1 minutes. While the overall pattern of change is similar, the differences in each household can be attributed to the characteristics of the occupants, such as thermal sensitiveness, economic situation (e.g., household income), BMI, and so on. The comfort base temperature, which is defined as the indoor air temperature corresponding to "neutral" thermal sensation (neither cool nor warm), was from 27.1°C to 27.9°C. Based on this, the entire time the occupant felt discomfort (δT) was 24.8 minutes on average. The average time the occupant felt discomfort before adaptive behaviour (δT_d) was 17.1 minutes, while the average time until the occupant recovered comfort (δT_c) was 5.9 minutes. The difference between δT_d and δT_c appears to be affected by the psychological adjustment factors such as the thermal expectation that the indoor thermal environment will be improved by the direct control of the occupant.

Discomfort capacity and comfort restoration were derived from the temporal dimension. Discomfort capacity (i.e., the average value: 42.5°C·min) was relatively larger than comfort restoration (i.e., the average value: 10.1°C·min). Interestingly, the correlation analysis between discomfort capacity and comfort restoration showed a significant positive correlation (Pearson correlation coefficient: 0.902, significance probability: 0.01). This means the greater the discomfort capacity of the household, the greater the comfort restoration of the occupant. Thus, in order to resolve the accumulated discomfort before the adaptive behaviour, it was found that the time for recovery of the indoor thermal environment was required as much as the discomfort.

In other words, the participants' showed a large tolerance to the build-up of thermal discomfort until they resorted to switching on air-conditioner, the action of which restored comfort relatively easily. Physical stimuli such as direct exposure to low-temperature air current emitted from the air-conditioner may have contributed to the rapid comfort restoration process in this research design. In addition, psychological adaptation factors such as being aware of air-conditioner operational status, therefore anticipating that the indoor thermal environment will be imminently improved, may also have contributed to these disparity between the discomfort build-up and discharge phases within each warm discomfort episode.

Based on our findings, the cooling strategy of residential buildings should establish to maximise potential energy savings while ensuring the thermal comfort of the occupants.

4. Conclusions

Adaptive behaviour (the operation of the air-conditioner) occurs due to the discomfort of the occupant. This study quantitatively examined discomfort capacity and comfort restoration by analysing changes in temporal dimension and indoor thermal environment based on occupant comfort regarding the occurrence of adaptive behaviour. Across the entire study we found that the average thermal discomfort episode (δT) lasted 24.8 minutes. The average discomfort tolerance duration prior to an air-conditioner switch-on behaviour (δT_d) being 17.1 minutes, compared to the average time required for the restoration of occupant comfort after the air-conditioner behaviour was initiated (δT_c) being 5.9 minutes. The findings indicated that the 'discomfort capacity' integral was approximately 4.2 times larger than the ' comfort restoration' integral. Our findings have practical implications in setting up dynamic control strategies that are more responsive to occupant real-time comfort demands.

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