

Article

Effect of Different HVAC Control Strategies on Thermal Comfort and Adaptive Behavior in High-Rise Apartments

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Abstract: In the residential sector, householders play an active role in regulating the indoor climate via diverse control measures such as the operation of air-conditioners or windows. The main research question asked in this paper is whether control decisions made by householders are rational and effective in terms of achieving comfort and energy efficiency. Based on a field study in South Korea, this paper explores how a HVAC control strategy for high-rise apartment buildings can affect occupant comfort and adaptive behavior. Two different control strategies: (1) occupant control (OC), where occupants were allowed to freely operate the HVAC system and (2) comfort-zone control (CC), where the operation of the HVAC system was determined by the researcher, based on a pre-defined comfort zone, were applied to, and tested within the participating households in summer. The impact of the two control strategies on indoor thermal environments, thermal comfort, and occupant adaptive behavior were analyzed. We find that the CC strategy is more energy/comfort efficient than OC because: (1) comfort was achieved at a higher indoor temperature, and (2) unnecessary control behaviors leading to cooling load increase can be minimized, which have major implications for energy consumption reduction in the residential sector.



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1. Introduction

In addition to improving energy consumption efficiency, a primary focus area of building design and operation is the maintenance of the health and comfort of building occupants who stay indoors for at least 80% of the day [1]. In this regard, occupant thermal comfort is considered as one of the essential criteria when evaluating building performance [2]. Occupants' subjective evaluation of heating or cooling, measured via surveys, is typically used as an index to judge and predict indoor thermal environment [3,4]. Factors influencing thermal comfort are important in determining the energy consumption of the environmental systems in a building [5], which are known to account for as much as 20% of the variance of the overall building energy consumption [6].

Thermal adaptation refers to the reactions of an occupant to indoor discomfort in an attempt to re-establish comfort [7]. Since the range of thermally acceptable conditions varies, depending on occupants' adaptability, the concept of thermal adaptation becomes critical in the broader context of comfort/energy efficiency [8,9]. Occupants' adaptive comfort behavior can be regarded as the feedback loop connecting the occupant and the indoor thermal environment of the occupied space [10,11]. Occupant adaptive behaviors may directly affect the energy consumption of a building, and maladaptive behavior is often associated with excessive energy consumption [10]. In this regard, recent studies have attempted to determine the causal parameters driving occupant adaptive behavior in order to improve the predictive skill of building energy models and simulations [12–15].

Adaptive behavior can be determined by both physical environmental and nonphysical factors such as thermal history, thermal expectation, culture and habits [10]. Adaptive

behaviors such as window opening/closing, air-conditioning system usage, and change of clothes can ameliorate occupant thermal discomfort. Therefore, analysis of the effects of occupant adaptive behaviors on their thermal comfort becomes useful [16,17]. The indoor environment management strategy should be based upon active integration of occupant thermal comfort and related behaviors into the design concept and operation of a building [18]. Despite previous efforts to establish simulation models of occupants' behavior [14,15,19–23], the underlying mechanisms connecting adaptive behavior to subjective thermal comfort is yet to be fully understood [16,24]. Most of the behavior models consider only the influence of deterministic physical environmental variables [10]. Also, as these studies have mostly focused on commercial or public building typologies, such as offices and hospitals, there is a paucity of adaptive thermal behavioral models in residential contexts [25].

Particularly in residential buildings, occupant adaptive behaviors can be strongly driven by household financial circumstances [26]. In comparison with other building typologies, occupants of residential buildings such as apartments tend to wear more varied clothing insulation and engage in diverse physical activity levels. Residents also tend to report more varied neutral temperatures indoors [11,27,28]. While householders determine the operation of an air conditioning system (AC) by considering both comfort and economy, it is questionable whether their decisions are as rational as assumed in building simulations. Moreover, in many apartment buildings, HVAC (heating, ventilation, and air conditioning) systems do not allow occupant centric control of the initial temperature settings, and most occupants are continuously exposed to a predetermined narrow temperature range [25,29,30]. Thermal comfort guidelines tend to vary between different countries, and each country has implemented different laws, regulations and/or recommendations according to its climatic and cultural background. The conventional building standards of South Korea does not adequately reflect scientific findings on occupant thermal comfort and behavior in apartment buildings [31]. In South Korea, the lower limit of cooling setpoint temperature of 26 °C is universally applied for nearly all kinds of buildings [32], which stands in stark contrast with other regions, particularly western countries.

Considering these characteristics, the HVAC control method suitable for apartment buildings should be established. Attempts to recognize and reflect the thermal comfort of occupants are continued in the standards of the HVAC system operation [30,33–35]. Occupants' thermal comfort is one of the main driving factors in defining the operational settings of HVAC systems, and it greatly impacts energy efficiency in buildings [36]. Therefore, if occupants' responses toward the surrounding thermal environment (e.g., thermal sensations, comfort range, thermal preference, physiological responses et al.) are reflected as input parameters for HVAC system operation, the potentials of operational efficiency can be improved by reducing the reliance on mechanical systems in the provision of comfort [37–39]. Such attempts have been used as feedback in the control of HVAC systems, with an aim to provide improved thermal satisfaction and energy efficiency by avoiding over-conditioning [36,38,40]. As a result of such comfort-driven operation strategy that reflects the individual's thermal preference and history, compared to the conventional operation strategy, the previous findings demonstrated that energy efficiency and improvement of the thermal comfort were simultaneously achievable [40,41]. Accordingly, in this paper, we hypothesized that occupant comfort demand could be leveraged for a more efficient control strategy.

In this paper, we report the results of field observations involving actual householders of apartment buildings in Daegu, South Korea. The primary purpose of our field investigation is to identify the effects of occupant adaptive behaviors on perception of thermal comfort under the two control strategies—i.e., one based on the government setpoint guideline assumed to be universally applicable across all building typologies and the other based on pre-defined comfort zone of apartment residents. Focus is on understanding the relationship between variations in indoor thermal environmental parameters, occupant perception of thermal comfort, adaptive behavior, and AC system operation modes under

the two different scenarios. The expected research outcome is a contribution to establishing evidence-based and energy-efficient control strategy for the indoor thermal environment of apartment buildings in the Korean climatic and cultural context.

2. Methods

In order to objectively verify the impact of the control strategy of the HVAC system on occupant comfort and associated behaviors, the occupant control (OC) mode utilizing the existing recommended indoor setpoint air temperature (26 °C) in the Korean regulatory body was set as the control-group condition, while the comfort-zone control (CC) strategy based on a comfort range derived by considering the actual occupant thermal comfort status was set as the experimental-group condition. Changes in the physical indoor thermal environmental parameters, occupant thermal comfort indices, generation of adaptive behavior, and HVAC system operation status were comparatively analyzed in accordance with the two control modes addressed above. Figure 1 depicts the overall research design.

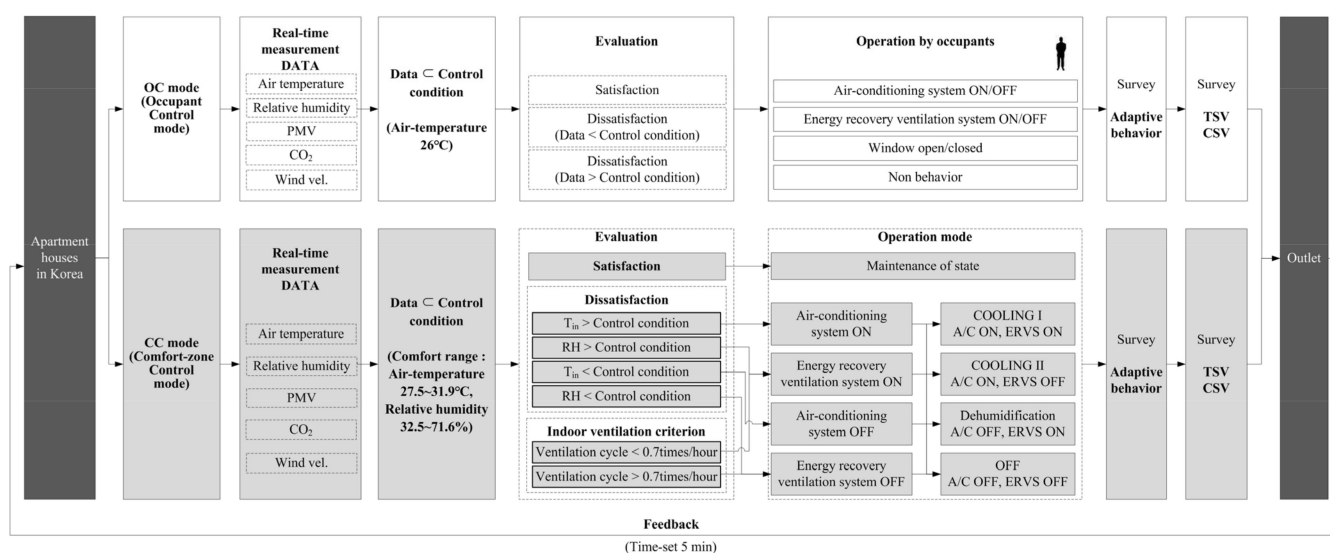


Figure 1. Flow diagram of experiment process (T_{in} : Indoor air-temperature, RH: Relative humidity, PMV: Predicted-Mean-Vote, TSV: Thermal-Sensation-Vote, CSV: Comfort-Sensation-Vote, A/C: Air-conditioning system, ERVS: Energy-Recovery-Ventilation-System).

In this experiment, under occupant control (OC) conditions the AC system was operated at a specific indoor temperature. The participant group exposed to the OC mode was set as the control group, and the indoor temperature on the thermostat of each participating home was set at 26 °C, which is the prescribed lower limit of the indoor air temperature for AC system operation in South Korea [32]. To reflect the real-life situations, this control mode assumed that there was no restriction on occupant adjustment of the indoor environment. In other words, the operation of the HVAC system and windows was determined as per the occupants' will. Occupant adaptive behaviors and thermal comfort (thermal sensation vote (TSV) and comfort sensation vote (CSV)) were recorded together with the physical measurements of indoor thermal environment at 5 min interval.

Comfort-zone control (CC) mode is targeted at maintaining the optimal indoor thermal condition by modifying the physical parameters when it deviates from the pre-defined optimal range, applying the adaptive comfort concept. The CC approach is based on the findings of a field study carried out in high-rise apartment buildings in the same city of South Korea in which the occupant thermal comfort range was observed to be expanded through the process of adaptive behavior and thermal adaptation [42]. Thus, the thermal comfort range derived in the previous study was deemed suitable for the participant group in the current study. The comfort range in question exhibits a distribution of relatively high air temperatures and relative humidity levels as being located on the upper right side of

the psychometric chart in comparison with ASHRAE 55's comfort range [42]. In the current study, the comfort range is defined as the highest and lowest air temperatures of 31.97 °C and 27.54 °C ($\Delta T = 4.4$ °C) respectively, and the highest and lowest relative humidity levels of 71.66% and 32.56% respectively [42].

In the CC mode, HVAC system was controlled to meet the comfort criteria specified above and the minimum ventilation requirement for apartment buildings (0.7 times/h) [43]. The indoor thermal environment was evaluated every 5 min to repeatedly determine the operation mode of the HVAC system (i.e., Case 1: maintenance of the current state, Case 2: operation of both AC and energy recovery ventilation (ERV) systems, Case 3: operation of AC system, Case 4: operation of ERV system (for dehumidification and ventilation), Case 5: stoppage of both AC and ERV systems). Occupant adaptive behaviors and thermal comfort sensation (TSV, CSV) were surveyed at every stage.

3. Experiments

3.1. Field Survey

We conducted field studies in apartment blocks located in Daegu, South Korea. As illustrated in Figure 2, according to the National Climate Data Center, the summer air temperature range of Daegu over the three-year study period was the highest among those of South Korean cities [44]. Thus Daegu can be considered to represent the hottest summer weather characteristics of large cities in South Korea. In this regard, we note that as natural ventilation can lead to a large cooling load during summer in cities like Daegu, highlighting the importance of well-developed energy-efficient cooling and ventilation control strategy.

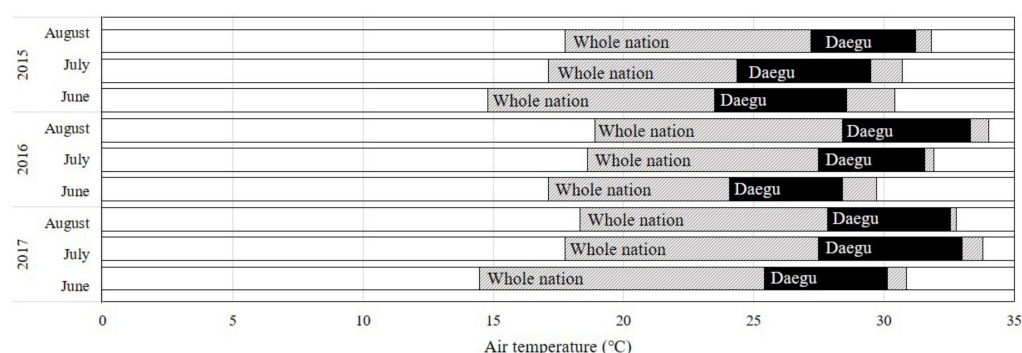


Figure 2. Temperature distribution over the three-year field study period in Daegu compared to the rest of South Korea [44].

As per the Korean government mandate of 2006, any apartment block with 100 or more households should have a mechanical ventilation system with a 24-h power supply [43]. In 2009, the relevant law was revised to recommend the use of a hybrid ventilation system combining natural ventilation and a mechanical ventilation system [43]. For the apartment blocks surveyed in this study, it was mandatory to install AC systems and mechanical ventilation systems, which satisfied the ventilation rate of 0.7 or more per hour and enabled 24-h continuous operation if necessary [43]. These apartment blocks were completed between 2009 and 2016.

The surveyed apartment blocks were evenly distributed across Daegu and showed diversity in the number of households, household and experimental area of each household, number of floors, and heat sources. Thus, these apartment blocks can be considered to comprehensively represent the general characteristics of an apartment in Daegu. Table 1 lists the general overview of our sample of apartment blocks, while Table 2 lists the mean demographics of subjects in the various apartment blocks surveyed in this study.

Table 1. Summary of investigated apartment block characteristics.

Block	District (gu/gun)	Household Area/ Experimental Area (m ²)	HVAC Specifications				Mode	Measurement Period
			Air-Conditioning System		Energy Recovery Ventilation System			
			Cooling Capacity (kW)	Cooling Area (m ²)	Air Volume (CMH)	Cooling Tempera- ture, Heat Transfer Efficiency (%, %)		
A1	Jung	113/40.68	6.5	52.8	150	70, 40	OC ¹	25 June 2015–27 June 2015
							CC ¹	28 June 2015–30 June 2015
A2	Buk	127/38.91	7.2	58.5	250	65, 35	OC	6 July 2015–8 July 2015
							CC	9 July 2015–11 July 2015
A3	Dalseong	106/38.16	6.0	48.8	150	70, 40	OC	20 July 2015–22 July 2015
							CC	23 July 2015–25 July 2015
A4	Dong	135/43.21	8.1	65.9	250	65, 35	OC	4 August 2015–6 August 2015
							CC	7 August 2015–9 August 2015
A5	Dalseong	82/35.28	5.2	42.3	150	75, 55	OC	28 June 2016–30 June 2016
							CC	1 July 2016–3 July 2016
A6	Dong	126/38.30	7.2	58.5	250	70, 50	OC	11 July 2016–13 July 2016
							CC	14 July 2016–16 July 2016
A7	Dalseo	165/47.88	9.0	81.8	360	70, 50	OC	25 July 2016–27 July 2016
							CC	28 July 2016–30 July 2016
A8	Dalseong	97/34.92	5.2	42.3	150	75, 55	OC	8 August 2016–10 August 2016
							CC	11 August 2016–13 August 2016
A9	Nam	109/37.24	6.5	50.2	250	70, 50	OC	10 July 2017–12 July 2017
							CC	13 July 2017–15 July 2017
A10	Dalseo	78/30.31	5.2	40.8	150	65, 35	OC	24 July 2017–26 July 2017
							CC	27 July 2017–29 July 2017
A11	Susung	162/43.09	9.0	81.8	360	55, 35	OC	7 August 2017–9 August 2017
							CC	11 August 2017–13 August 2017

¹ OC: Occupant control, CC: Comfort-zone control.**Table 2.** Mean demographics of subjects in various apartment blocks surveyed (A1–A11).

	No. of Occupants		Age (Year)		Height (m)		Weight (kg)		Clothing Insulation (clo)	
	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female
A1	2	2	43 (22.62) ¹	43 (19.79)	1.69 (1.41)	1.59 (4.97)	63 (1.41)	55 (7.07)	0.47 (0.03)	0.52 (0.03)
A2	2	2	43 (26.87)	45 (21.21)	1.75 (3.53)	1.61 (2.12)	72.5 (3.53)	60 (7.07)	0.49 (0.01)	0.51 (0.01)
A3	2	3	30 (4.24)	30.33 (2.30)	1.75 (7.77)	1.62 (2.51)	70 (11.31)	57.33 (4.61)	0.48 (0.04)	0.50 (0.01)
A4	2	3	40.5 (26.16)	37 (18.35)	1.75 (9.89)	1.64 (3.21)	72.5 (10.60)	60.66 (6.65)	0.49 (0.01)	0.51 (0.04)
A5	3	3	38 (6.24)	38 (18.24)	1.75 (2.08)	1.60 (9.59)	69.66 (4.72)	56.33 (10.21)	0.51 (0.01)	0.50 (0.01)
A6	2	4	42.5 (19.09)	32.5 (11.78)	1.76 (5.65)	1.64 (6.60)	90 (0)	58.5 (7.85)	0.49 (0.07)	0.50 (0.03)
A7	3	2	38 (19.05)	30 (1.41)	1.75 (5.03)	1.60 (3.53)	71.66 (10.59)	52.5 (10.60)	0.47 (0.03)	0.51 (0.01)
A8	2	3	48 (19.79)	41 (18.24)	1.71 (1.41)	1.59 (5.56)	71.5 (9.19)	55 (5)	0.52 (0.02)	0.52 (0.03)
A9	1	3	62	39 (14.16)	1.69	1.58 (0.47)	68.3	54 (4.54)	0.52	0.53 (0.02)
A10	2	2	45 (17.0)	42.5 (12.50)	1.80 (2.0)	1.61 (0.50)	66.5 (1.50)	61.5 (1.50)	0.50 (0.03)	0.52 (0.02)
A11	3	2	46.3 (16.1)	52 (13)	1.74 (1.24)	1.58 (3.0)	74 (4.92)	51.5 (1.5)	0.47 (0.02)	0.53 (0.01)

¹ Values in parentheses denote standard deviations.

3.2. Indoor Environmental Variables

We collected data from 08:00 to 20:00 (i.e., a period of 12 h) during which time most of daily living activities are executed. The OC strategy was used to control the indoor thermal environment via operation of the AC system (set-point temperature of 26 °C), ERV system, and windows according to occupant autonomous adaptive behaviors. Meanwhile, the CC strategy determined the operation mode of the HVAC systems via evaluation of the measurement of the indoor thermal environment. The ERV system was controlled to satisfy the ventilation rate of 0.7 times/h, as specified for apartment buildings [43]. In the CC mode, the ERV was used as the primary ventilation method and window opening was ruled out in order to avoid in a rapid increase of cooling and ventilation loads. Table 3 presents the details of the measuring instruments and measurements of the indoor environmental parameters.

Table 3. The measurement parameters and types of instruments used in field measurements.

Description	Instrument/ Sensor	Parameter	Range	Accuracy	Resolution
Data logger	TR-72Ui	Air temperature (°C)	−10–60 °C	±0.3 °C	0.1 °C
		RH (%)	10–95% RH	±5%	1% RH
Amenity Meter: PMV evaluation	AM-101	Air temperature (°C)	0–50 °C	±0.5 °C (at 15–35 °C)	0.1 °C
		Globe temperature (°C)	0–50 °C	±1.0 °C (at 15–35 °C)	0.1 °C
		Convection temperature (°C)	0–50 °C	from ISO 7726	0.1 °C
		RH (%)	10–90% RH	±3% RH (at 20–80% RH)	1% RH
		Air velocity (m/s)	0–1 m/s	±0.1 m/s	0.1 m/s
			1–5 m/s	±0.5 m/s	0.1 m/s
		Amount of clothing (clo)	0–2	-	0.1 clo
		Metabolic rate (met)	0.8–4.0	-	0.1 met
		PMV ¹	−3–+3	-	0.01
CO ₂ evaluation	TESTO 435	CO ₂ level	0–5000 ppm CO ₂	± (500 ppm CO ₂ ± 3% of mv)	1 ppm
			5000–10,000 ppm CO ₂	± (100 ppm CO ₂ ± 2% of mv)	1 ppm

¹ PMV: Predicted Mean Vote, PPD: Percentage of Persons Dissatisfied.

Our measurement protocols (physical measurements) followed the recommendations in ASHRAE Standard 55 ‘Thermal Environmental Conditions for Human Occupancy’ [45]. The measuring instruments used to monitor the thermal environment was placed 1.1 m above ground level.

Table 4 summarizes the measuring instruments and the locations at which the data were measured and collected.

Table 4. The locations at which the data were measured and collected.

Description	Time Interval	Each (EA)	Measuring Locations		Measuring Heights
Data logger	5 min	8	Indoor	Outdoor	1.1 m above ground level (Near the head when occupants are seated)
				The middle point of the living space	
				A distance of 1 m from the Air-conditioning system	
				A distance of 3 m from the Air-conditioning system	
				Outlet of the ERV ¹ system (1)	
				Outlet of the ERV system (2)	
				Outlet of the ERV system (3)	
PMV evaluation	5 min	1	Indoor	Outlet of the ERV system (4)	
				The middle point of the living space	
CO ₂ evaluation	5 min	1	Indoor	The middle point of the living space	
TSV, CSV check point	5 min	-	Indoor	The middle point of the living space	-
Adaptive behavior	Every moment	-	Indoor	At the point where adaptive behavior occurs	-

¹ ERV: Energy recovery ventilation.

3.3. Subjects and Survey Questionnaire

The participants' thermal sensation vote (TSV) and comfort sensation vote (CSV), which are the thermal comfort indices recommended by ASHRAE 55 and the Standard ISO 10551, were recorded every 5 min during the experiment [46,47]. TSV is computed for a 7-point scale from -3 to $+3$ with step intervals of 1 point, where -3 indicates 'cold', 0 corresponds to 'neutral', and $+3$ indicates 'hot' sensation. Similarly, CSV also uses a 7-point scale ranging from 1 to 7 in step intervals of 1 point, where 1 indicates 'very comfortable', 4 corresponds to 'neutral', and 7 indicates 'very uncomfortable' (Table 5). With regards to personal parameters of thermal comfort (i.e., clo and met), the participants were recommended to wear typical summer clothes (i.e., ~ 0.5 clo), and remain sedentary [34,35]. The average metabolic rate of the participants during the experiment was between 1.0 and 1.3 met.

Table 5. Thermal sensation vote (TSV) and comfort sensation vote (CSV) scale used in the study.

(a) TSV						
-3	-2	-1	0	1	2	3
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
(b) CSV						
1	2	3	4	5	6	7
Very comfortable	Comfortable	Slightly comfortable	Neutral	Slightly uncomfortable	Uncomfortable	Very uncomfortable

3.4. Adaptive Behavior According to Occupant Thermal, Comfort Sensation

Apartment occupants continually adapt themselves to, or modify their indoor thermal environment. If their adaptation strategy fails, the occupants experience discomfort. Adaptation can be classified into behavioral adjustment, physiological adjustment, and psychological adjustment [31] as follows:

- Behavioral adjustment: personal adaptation (clothing, activity, change of posture, etc.), control of indoor thermal environment, adjustment of cultural habits (clothing habits)
- Physiological adjustment: genetic adaptation, acclimatization
- Psychological adjustment: changes of thermal cognition and reaction to repetitive thermal stimulus

Various adaptive behaviors can occur simultaneously in an indoor space. In this study, we focused on the aspects of behavioral adjustment. The following adaptive behaviors were recorded during our field study:

- Adaptive behavior to improve indoor thermal environment: turning AC system on/off
- Adaptive behavior to improve ventilation: turning ERV system on/off, opening or closing window(s) (window behavior is exclusive to the OC mode)

During the monitoring period, we acquired physical measurements of the indoor thermal environment, occupants' subjective thermal comfort data and their behavioral data for the subsequent analysis to explore the relationship between those aspects in the context of high-rise apartment buildings in South Korea.

4. Results

4.1. Subjective Thermal Responses

The distribution of TSV, CSV under the two control modes (OC and CC) is presented in Figure 3.

The average TSV values, which indicate the occupant thermal sensation, were -0.22 ($SD = 1.06$, $N = 244$) for OC and -0.74 ($SD = 1.18$, $N = 237$) for CC. TSV_{OC} tended to be concentrated around 0 (neutral, 35.4%). As for the percentages corresponding to the remaining points of the scale in the OC mode, cooler-than-neutral sensations (-3 , -2 ,

−1) accounted for 39.5% and warmer-than-neutral sensations (1, 2, 3) accounted for 25.1% of the participant responses. Meanwhile, TSV_{CC} corresponded to the largest percentage of 27.9% for −2 (Cool), immediately followed by 26.9% for 0 (Neutral). Among all the TSV_{CC} raw data, cooler-than-neutral sensations (−3, −2, −1) formed the majority (56.8%) response. On the other hand, warmer-than-neutral sensations (1, 2, 3) were as low as 16.4% of the total responses.

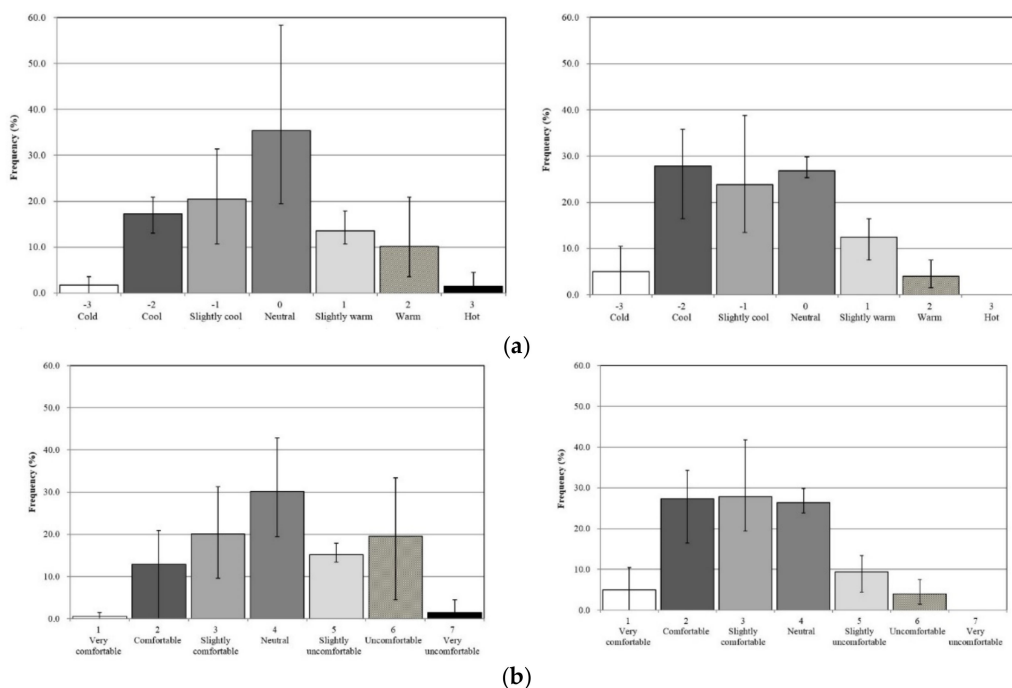


Figure 3. Distribution of Thermal sensation vote (TSV) and Comfort sensation vote (CSV) under different control methods. (a) TSV (Left: Occupant Control mode, Right: Comfort-zone Control mode). (b) CSV (Left: Occupant Control mode, Right: Comfort-zone Control mode).

Regarding comfort sensation votes, the average CSV values were 4.11 (SD = 1.03, N = 244) for OC and 3.26 (SD = 1.20, N = 237) for CC. As in the case of TSV_{OC} , CSV_{OC} exhibited the same concentration around 4 (neutral), which accounted for 30.2% of the responses. The ‘comfortable’ sensation (1, 2, 3) accounted for 33.7% while the ‘uncomfortable’ sensation (5, 6, 7) accounted for as much as 36.3%. CSV_{CC} exhibited a trend similar to TSV_{CC} . The ‘comfortable’ sensation (1, 2, 3) accounted for 60.3%, the neutral sensation (4) accounted for 26.4%, and the ‘uncomfortable’ sensation (5, 6, 7) corresponded to only 13.5% of all responses. This meant that the majority of responses corresponded to ‘comfort’ in the CC mode.

4.2. Correlation between Indoor Thermal Environment and Thermal Comfort

During the monitoring period the measured indoor temperature exceeded 26 °C, which is recommended as the lower limit of the indoor air temperature in South Korea. The observed temperatures also tended to be higher than the ASHRAE 55’s summer comfort range (23–26 °C). The average indoor air temperature for CC was 27.8 °C, which was slightly higher than the average value of 27.2 °C for OC. The average indoor relative humidity was 45.4% in the CC case and 46.1% in the OC case. In the OC case the cooling load seemed to increase rapidly given the large deviation and variance observed in temperature and humidity, compared to the CC mode. This is presumably due to occupants’ window opening behavior under the OC model.

Next, we performed a correlation analysis to identify key physical parameters associated with occupant perception of the thermal environment (i.e., TSV and CSV, Table 6) under the two control scenarios (OC and CC).

Table 6. Correlation between TSV, CSV and physical parameters of indoor environment.

		Thermal Sensation Vote (TSV)		Comfort Sensation Vote (CSV)	
		Occupant Control Mode	Comfort-Zone Control Mode	Occupant Control Mode	Comfort-Zone Control Mode
Temperature	Pearson's correlation coefficient	0.619	0.746	0.457	0.748
	<i>p</i> -value	0.000	0.000	0.000	0.000
	N	218	201	218	201
Relative Humidity	Pearson's correlation coefficient	0.295	0.546	0.102	0.542
	<i>p</i> -value	0.000	0.000	0.132	0.000
	N	218	201	218	201
CO ₂	Pearson's correlation coefficient	−0.218	−0.315	0.159	−0.309
	<i>p</i> -value	0.001	0.000	0.019	0.000
	N	218	201	218	201

The result of the analysis revealed that the indoor air temperature exhibited a positive and relatively high correlation with TSV and CSV. When CC was applied instead of OC, the indoor air temperature exhibited a higher correlation with occupant thermal/comfort sensations.

Relative humidity also had a significant correlation with the occupant comfort sensation, suggesting that it needs to be considered to determine an appropriate indoor thermal environmental control strategy. The relative humidity in the CC case was strongly correlated with the TSV and CSV indices, while that in the OC case was weakly correlated with TSV and exhibited no statistical significance as regards CSV. When the relative humidity is high, operating the HVAC system on the dehumidification mode is one of the effective control strategies to enhance the comfort level. As the OC strategy involved occupant autonomous operation of HVAC without considering the relative humidity, the occupant TSV and CSV appeared to be negatively affected.

Here, we remark that a higher CO₂ concentration in an indoor space corresponds to reduced occupant comfort. In this regard, CC exhibited a low negative correlation with CO₂ concentration. On the other hand, the OC strategy did not yield any significant correlation between CO₂ and TSV/CSV.

4.3. Variation of Adaptive Behavior According to Control Method

Table 7 classifies the purpose of operating an HVAC system into two categories: (1) the improvement of the thermal environment and (2) the improvement of ventilation. If there was no adaptive behavior occurred, it was referred to as non-behavior in Table 7.

Table 7. The occurrence of adaptive behavior under the two control modes.

Control Method	Adaptive Behaviors	Percentage (%)
Occupant Control	The behaviors of improving thermal environment (AC)	67.1
	The behaviors of improving ventilation (ERV or windows)	26.5
	Non-behavior	6.4
Comfort-zone Control	The behaviors of improving thermal environment (AC)	47.1
	The behaviors of improving ventilation (ERV)	23.5
	Non-behavior	29.4

When OC was applied, a majority of adaptive activities (67.1%) comprised attempts to improve the indoor thermal environment. On the other hand, the activities of improving ventilation were less frequently observed (26.5%). When windows were opened by the occupants (for the purpose of ventilation), hot outside air flowed into the indoor spaces, resulting in a rapid increase of the cooling load. It seemed that the occupants' behaviors of improving ventilation for a short time led to triggering the behaviors of improving thermal environment, resulting in the high percentage of the thermal adaptive activities recorded during the OC mode. The OC approach registered a large fluctuation of indoor thermal environment, which then led to occupants' frequent responses of thermal discomfort.

When CC was applied, control strategies towards improving the indoor thermal environment accounted for 47%, those of improving ventilation accounted for 23%, and non-activity accounted for 29%. In comparison with OC, CC led to less frequent operation of air-conditioning. The relatively high percentage of non-activity in the CC case is attributable to reduced demand for control behaviors.

The participants' adaptive behaviors to improve indoor thermal environment and ventilation occurred in various ways. In some cases, the AC system, ERV system, and windows were separately operated. At other times, multiple behavioral adjustments occurred simultaneously. Figure 4 presents the schematic of the frequencies of adaptive behaviors in each case under the OC and CC modes.

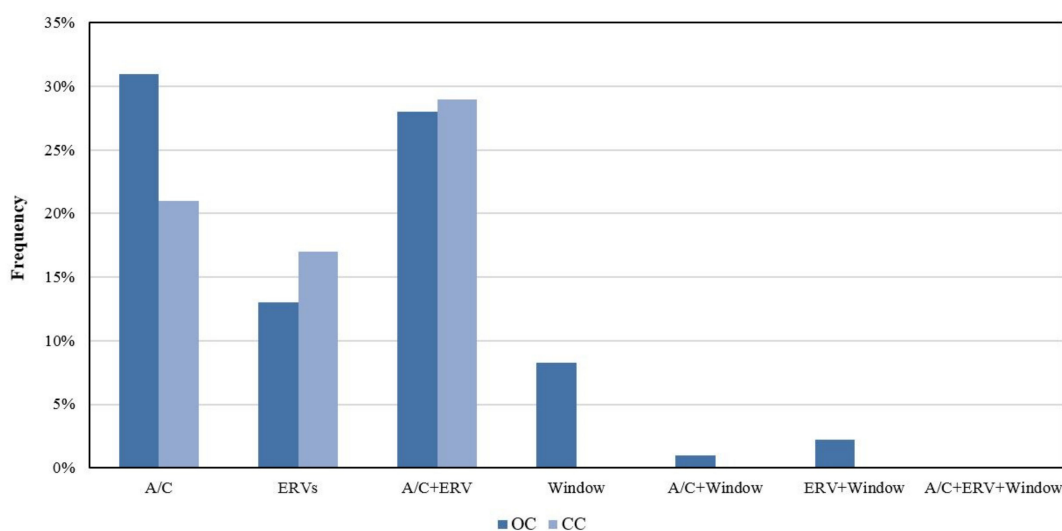


Figure 4. Frequency distribution for adaptive behaviors (OC: Occupant control, CC: Comfort-zone control, AC: Air-conditioning system, ERVs: Energy recovery ventilation system).

The operation of the AC system alone accounted for the largest portion of the adaptive behaviors in the OC mode, followed by the simultaneous operation of the AC and ERV systems, operation of the ERV system alone, window opening, simultaneous operation of the ERV system and window opening, and simultaneous operation of the AC system and window opening. The window opening behavior led to increase in the indoor cooling load, which then increased the operation rate of the AC system at the same time. Here, we note that when the AC system was operating, the windows were usually closed. However, when the OC strategy was applied, the windows were sometimes opened even when the AC system was operated. This was because the inflow of fresh air was necessary due to household activities such as cooking, or simply because occupants forgot to close the window.

When the CC strategy was applied, the simultaneous operation of the AC and ERV systems was observed most frequently, followed by operation of the AC system alone and that of the ERV system alone. In contrast to the OC approach, the simultaneous operation of the AC and ERV systems as well as the operation of ERV system alone accounted for larger percentages in the CC case. Moreover, the demand for the operation of the ERV

system significantly increased in order to satisfy the standard of the ERV system operation, that is, 0.7 times/h.

In order to understand the relationship between adaptive behaviors occupant perceived thermal comfort, the occurrence rates of adaptive behaviors corresponding to each category of TSV or CSV are plotted in Figures 5 and 6.

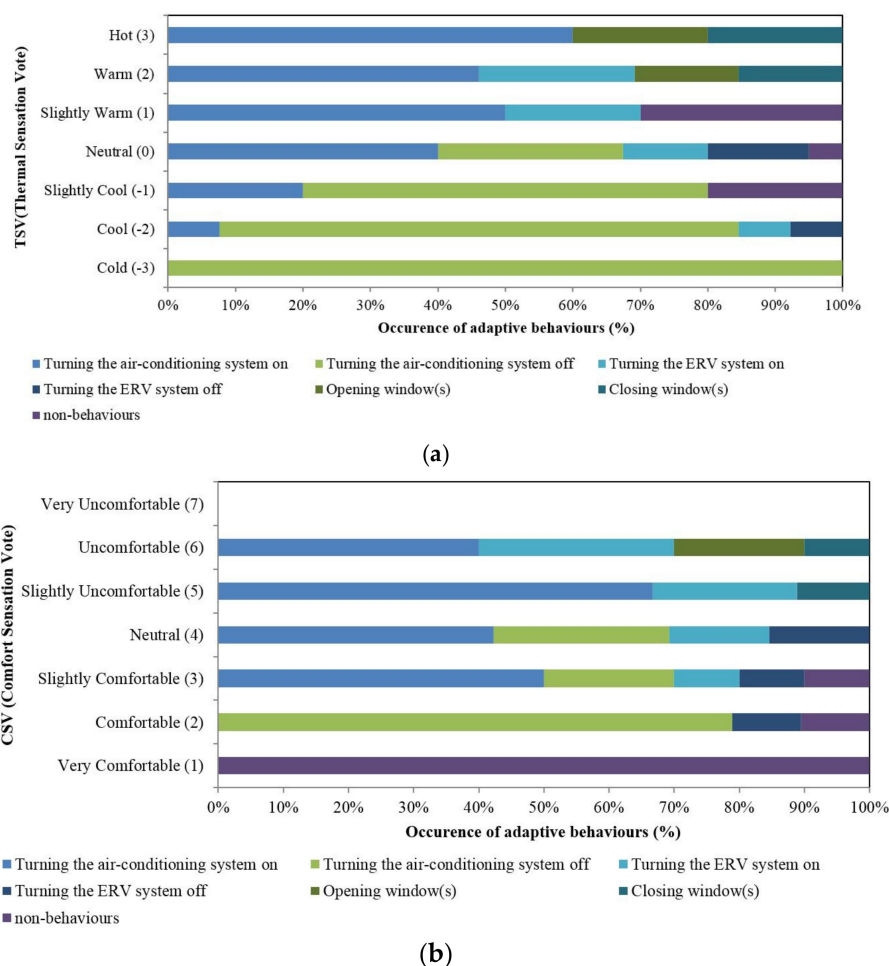


Figure 5. The occurrence rate of adaptive behavior in the Occupant Control mode (TSV_{OC}: Thermal Sensation Vote in Occupant Control mode, CSV_{OC}: Comfort Sensation Vote in Occupant Control mode). (a) Adaptive behaviors in relation to TSV_{OC}. (b) Adaptive behaviors in relation to CSV_{OC}.

In the OC case, many activities to improve the indoor thermal environment frequently occurred when occupants felt ‘hot’ or ‘uncomfortable’. They often chose to open/close windows to immediately resolve the discomfort issue. However, this did not improve the indoor thermal environment but caused a large cooling load, which resulted in excessive operation of the AC system.

On the other hand, when the CC strategy was applied, even when the TSV and CSV indices were ‘neutral’, the AC system was operated. Nevertheless, the frequency and duration of AC operation was relatively low and this is because the indoor thermal environment index satisfied the pre-defined comfort range again in a short time.

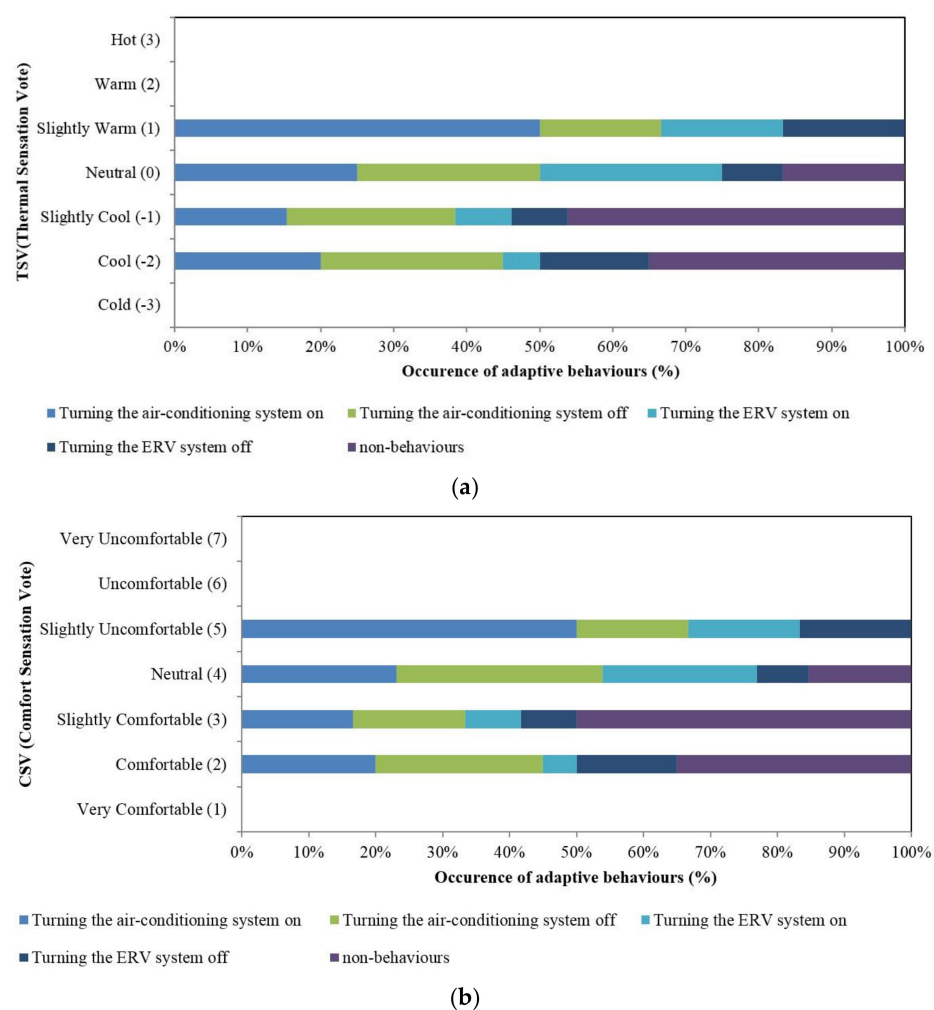


Figure 6. The occurrence rate of adaptive behavior in the Comfort-zone Control mode (TSV_{CC} : Thermal Sensation Vote in Comfort-zone Control mode, CSV_{CC} : Comfort Sensation Vote in Comfort-zone Control mode). (a) Adaptive behaviors in relation to TSV_{CC} . (b) Adaptive behaviors according to CSV_{CC} .

4.4. Relationship between Adaptive Behavior and Physical Environmental Parameters

Figure 7 illustrates the distribution of the operation rates of the HVAC system according to indoor air temperatures.

As can be seen in Figure 7a, the AC operation rate increases along with increase in the indoor air temperature. When the indoor air temperature is higher than a certain value, the operation rate reaches 1.0. AC system operation alone occurs first at the indoor air temperature of 25 °C when the OC strategy is applied. On the other hand, when the CC strategy is applied, the requirement for AC system operation is first registered at 26.7 °C. When the operation rate of the AC system reached 1.0 for the first time, the indoor air temperature was 30.1 °C in the OC mode and 32.6 °C in the CC mode.

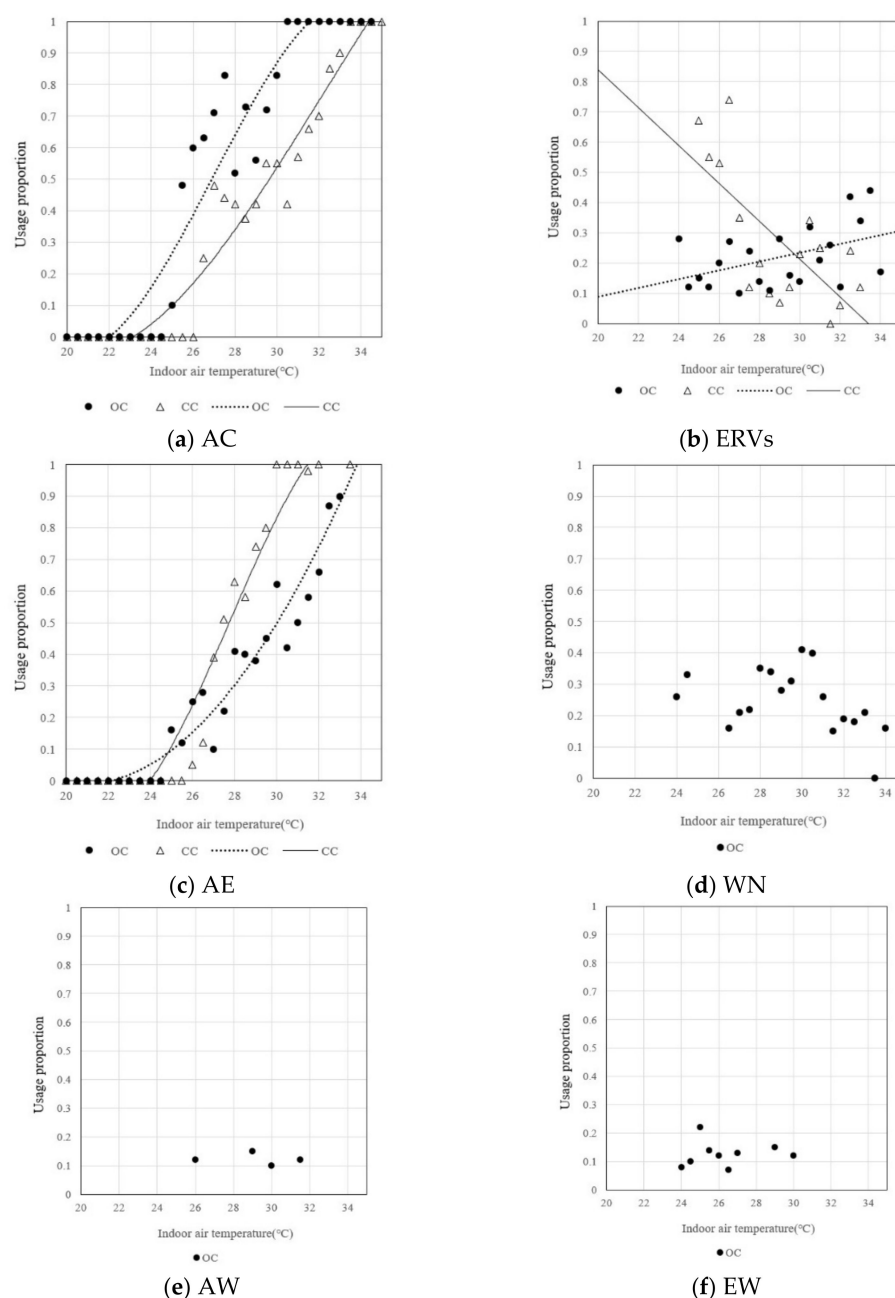


Figure 7. The distribution of the operation rates of the HVAC system in relation to indoor air temperatures (OC: Occupant control mode, CC: Comfort-zone control mode, AC: Air-conditioning system, ERVs: Energy recovery ventilation system, AE: Air-conditioning system and Energy recovery ventilation system, WN: Window, AW: Air-conditioning system and Window, EW: Energy recovery ventilation system and Window).

Figure 7b shows that the operation of the ERV system alone is first generated for the OC case, and the operation rate generally increases with increase in the indoor air temperature. It seemed that the occupants had the expectation that the operation of the ERV system would improve (i.e., cool) the indoor thermal environment.

In some cases, occupants operated both the AC and ERV systems and then turned off the AC system. On the other hand, in the CC case, the standalone operation of the ERV system was inversely proportional to increase in the indoor air temperature. Because a certain level of ERV operation was necessary to meet the indoor ventilation standard, both the AC and ERV systems were operated simultaneously as the indoor air temperature exceeded about 27 °C.

In Figure 7c, the simultaneous operations of the AC and ERV systems exhibit a similar increasing trend of operation rate with increasing indoor air temperature in the two control modes. Unlike the standalone operation of each system, the rate of simultaneous operation is higher for CC from the indoor air temperature of 27.5 °C.

From Figure 7d, we note that window opening is restricted to the OC case, and there is no clear trend to be observed. Also, simultaneous operation of AC and windows (Figure 7e), or AC and ERV (Figure 7f) were observed in the OC mode. However, again, there was no clear relationship between those control behaviors and the indoor air temperature variations.

5. Discussion

In order to improve thermal comfort in the living space, a suitable AC control strategy that reflects the thermal comfort requirements of occupants is necessary. It is also important to determine which index to be used as a criterion for controlling the indoor thermal environment. Neutral temperature, which is defined as the indoor temperature corresponding to “neutral” thermal sensation (neither cool nor warm), reflects the thermal comfort requirement of the occupant [48]. This study derived neutral temperatures for the OC and CC cases and compared them against each other. The neutral temperature was then utilized to evaluate the adequate degrees of OC and CC application as the control modes of HVAC systems.

Neutral temperatures were derived by performing the linear regression analysis with the indoor operative temperature (T_{op}) as the independent variable and TSV/CSV as the dependent variable. Table 8 presents the regression analysis results.

Table 8. Linear regression analysis.

Mode	Dependent Variable	Independent Variable	B	R ²	T	P	VIF
Occupant Control mode	TSV ¹	(constant)	−10.975				
		T_{op} ¹	0.391	0.384	11.597	0.000	1.000
	CSV ¹	(constant)	−4.6786				
		T_{op}	0.322	0.209	7.554	0.000	1.000
Comfort-zone Control mode	TSV	(constant)	−11.256				
		T_{op}	0.379	0.557	15.821	0.000	1.000
	CSV	(constant)	−1.840				
		T_{op}	0.192	0.529	14.961	0.000	1.000

¹ TSV: Thermal Sensation Vote, CSV: Comfort Sensation Vote, T_{op} : Indoor Operative temperature.

The equations derived from the regression analysis are presented as Equations (1)–(4). Neutral temperature largely depends on the distance of the actual sensation from the neutral point, as given by the following equations:

The regression equation for the OC mode is as follows:

$$TSV_{OC} = -10.98 + 0.39 \times T_{op} \text{ (Neutrality} = 28.1 \text{ °C)} \quad (1)$$

$$CSV_{OC} = -4.68 + 0.32 \times T_{op} \quad (2)$$

The regression equation for the CC mode is as follows:

$$TSV_{CC} = -11.26 + 0.38 \times T_{op} \text{ (Neutrality} = 29.7 \text{ °C)} \quad (3)$$

$$CSV_{CC} = -1.84 + 0.19 \times T_{op} \quad (4)$$

Therefore, when TSV equals zero, the neutral temperature is equal to the substituted temperature. Figures 8 and 9 show the scatter plots of the distribution of the occupant TSV and CSV, and the accompanying regression lines.

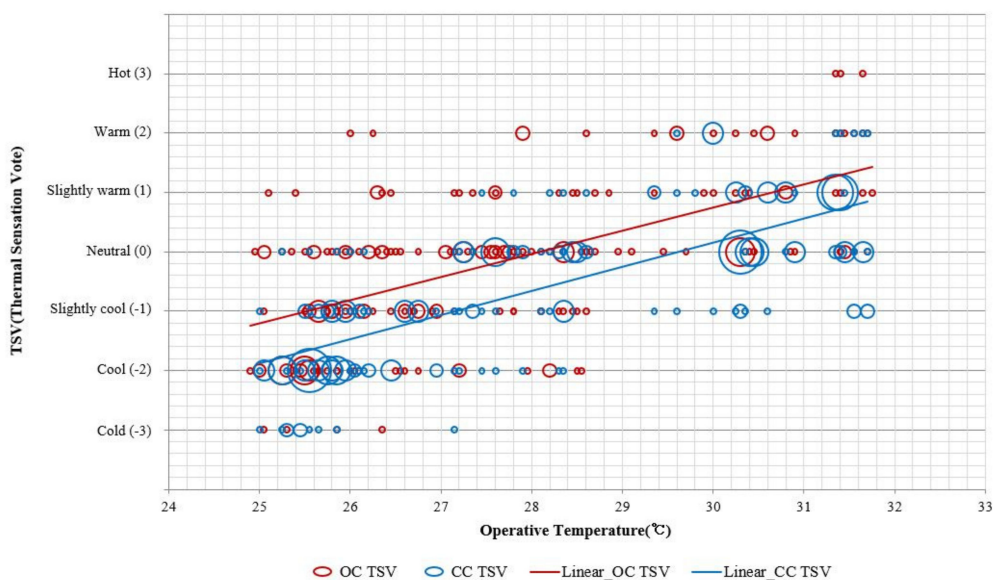


Figure 8. Thermal sensation votes in relation to indoor operative temperature, OC mode (red solid line) and CC mode (blue solid line).

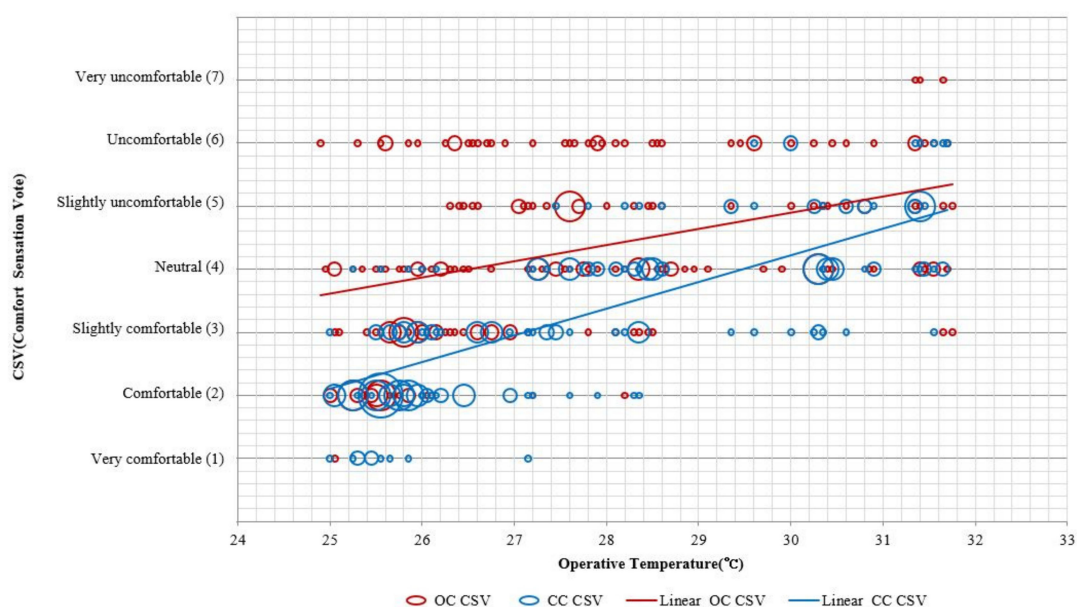


Figure 9. Comfort sensation votes in relation to indoor operative temperature, OC mode (red solid line) and CC mode (blue solid line).

As for the distribution of TSV in relation to indoor operative temperatures, the trend lines of OC (0.39 vote/°C) and CC (0.38 vote/°C) exhibit similar gradients. However, the operative temperature corresponding to the same TSV value is higher for CC by about 1.6 °C. The occupants' neutral temperature calculated using Equations (1) and (3) was about 1.6 °C higher in the CC mode (29.7 °C) than in the OC mode (28.1 °C).

As for the CSV distribution according to operating temperatures, the trend line of the CC (0.19 vote/°C) exhibits a gentler gradient than that of OC (0.39 vote/°C). When OC was applied, the occupant discomfort increased more rapidly along with increase in

temperature. This result indicates that in the case of OC, occupants are more sensitive to temperature change. As in the case of TSV, the operative temperature corresponding to the same CSV value tended to be higher in the CC mode. This indicates that occupants can retain their thermal equilibrium for a longer time under the CC strategy. In the CC mode, even if the AC system stops operating and the indoor temperature increases, occupants seem to retain their thermal equilibrium for a longer time than in the OC case. In the CC mode, occupant votes are concentrated around the ‘cool’ and ‘comfortable’ categories on the rating scale, and the indoor temperature and subjective thermal comfort indices exhibit a smaller variation. Therefore, CC is found to be more advantageous to occupants with respect to maintaining thermal comfort.

Interestingly, the neutral temperatures derived from our sample of households in Daegu city (known as the hottest city in South Korea) exceeded 26 °C, which is recommended as the lower limit of indoor temperature in South Korea. This means that the 26 °C indoor temperature guideline is realistic in terms of providing comfort to sedentary occupants in high-rise apartment buildings, given that appropriate HVAC control strategy is established. Table 9 lists the findings of existing studies on the comfort temperature for the summer season.

Table 9. Summary of study into comfort temperatures.

Authors	Country	Building Type	Season of Experiment	N	T _c (°C) ¹
Heidari and Sharples [49]	Iran	Residential	Summer (July, August)	-	28.4
Rijal et al. [50]	Japan	Residential	Summer	13,471	26.1
Nakaya et al. [51]	Japan	Residential	Summer	70	27.6
Katsuno et al. [52]	Japan	Residential	Summer	1093	27.1
Yoshimura et al. [53]	Japan	Residential	Summer	-	29.1
Rijal et al. [54]	Nepal	Residential	Summer	103	21.1–30.0
Rijal and Stevenson [55]	UK	Residential	Summer	235	22.9
Rangsiraksa [56]	Thailand	Residential	Summer	687	25.2
Anupama et al. [57]	India	Residential	Summer	-	27.4
Feriadi and Wong [58]	Indonesia	Residential	Summer	525	29.1
Han et al. [59]	China	Residential	Summer	110	28.6
de Dear et al. [60]	Australia	Residential	Summer	1525	22–24
Nicol and Roaf [61]	Pakistan	Residential, office	Summer	4927	28.2
Damaiti et al. [62]	Malaysia	Office	Summer (March, April, May)	1114	25.6
Indraganti et al. [63]	Japan	Office	Summer (July, August, September)	1979	26.4
Damaiti et al. [64]	Singapore	Office	Summer (January)	14	26.4
Mustapa et al. [1]	Japan	Office	Summer (August)	222	26.6
Damaiti et al. [62]	Japan	Office	Summer (September)	418	25.8
Madhavi et al. [64]	Qatar	Office	Summer	1850	24.2
Damaiti et al. [62]	Indonesia	Office	Summer (February, March)	91	26.3

¹ T_c: Comfort temperature.

The previous studies included in Table 9 are categorized by building types—i.e., residential buildings and office buildings. Our literature search indicated that the comfort temperature in residential buildings is higher than that in office buildings. This difference is attributable to contextual differences such as clothing behavior, activity level, and degree of control.

When the comfort temperature as reported by an existing study for residential buildings (Table 9) was compared with the neutral temperature derived from OC in this study (28.1 °C), it was found to be similar. On the other hand, the neutral temperature derived from CC in this study (29.7 °C) was higher than most of the neutral temperatures reported

by the existing studies. Although similar types of buildings were examined under similar seasonal conditions, the neutral temperatures were different. This is probably because each country has different indoor cultural practices and different heating/AC systems. In particular, in South Korea, the floor-sitting culture, wherein people take off shoes at home, can affect their comfort perception.

Based on our findings, we can state that with the application of the CC strategy, unnecessary operation of the AC and ERV systems can be prevented, appropriate level of ventilation can be maintained, and thermal comfort can be maintained at a higher temperature, which in turn will reduce HVAC energy consumption. The results of this study are consistent with the results of other studies that the operating efficiency was improved during HVAC operation by reflecting the thermal comfort of actual occupants [36].

6. Conclusions

We conducted field tests over a certain period during which the control modes of OC and CC for HVAC systems were applied to actual apartment blocks. The instrumental data for the two cases were compared against the thermal comfort indices, adaptive control behavior, and the mode of HVAC system operation. Then the effectiveness of the two different control strategies was examined. The key findings of our study can be summarized as follows:

- When CC was applied, the physical indices of the indoor thermal environment (i.e., temperature and humidity) exhibited a higher correlation with occupant subjective responses (i.e., TSV and CSV) than when OC was applied.
- The operation of the HVAC system was classified into six cases (AC system operation alone, simultaneous operation of AC and ERV systems, operation of ERV system alone, window opening, simultaneous operation of ERV system and window opening, and simultaneous operation of AC system and window opening). We found that the OC mode corresponded to a high percentage of discomfort responses and triggered more frequent adaptive behaviors, compared to the CC mode.
- A quantitative analysis was conducted to estimate how occupant thermal comfort was affected by the operation method of the HVAC system. The CC mode was more effective than the OC mode in maintaining occupant thermal comfort.
- A linear regression analysis was also performed to calculate neutral temperatures. The neutral temperature in the CC mode was higher than that in the OC mode. This indicates that when CC is applied to control the HVAC system, occupant thermal comfort can be achieved at a higher indoor temperature.

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Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki. Nonetheless, ethical review and approval were waived for this study, due to the characteristics of the study: no medical experiments were performed on human; Subjects were informed of the objectives of the study and expressed their consent by self-enrolling in the survey; occupants' data was collected under written given consent; data was anonymised.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from authors.

Conflicts of Interest: The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Abbreviations

TSV	Thermal sensation vote
TSV _{oc}	The surveyed TSV in OC mode
TSV _{cc}	The surveyed TSV in CC mode
CSV	Comfort sensation vote
CSV _{oc}	The surveyed CSV in OC mode
CSV _{cc}	The surveyed CSV in CC mode
PMV	Predicted mean vote
OC	Occupant control
CC	Comfort-zone control
HVAC	Heating, ventilation, and air conditioning systems
AC	Air conditioning system
ERVs	Energy recovery ventilation system
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
CLO	The clothing insulation
SD	Standard deviation
T _{in}	Indoor air temperature (°C)
T _{op}	Indoor operative temperature (°C)
T _{out}	Outdoor mean temperature (°C)
T _c	Comfort temperature (°C)
RH	Relative humidity (%)
AE	Air-conditioning system and Energy recovery ventilation system
WN	Window
AW	Air-conditioning system and Window
EW	Energy recovery ventilation system and Window

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