

Research on cooling control behavior and thermal environment in Korean households, focusing on a comparative study over 20 years

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SUMMARY

This study examines how cooling air conditioner usage behavior and indoor thermal environments in households in Seoul and the metropolitan area have changed over approximately 20 years by conducting the same survey in 2024 as those conducted in the summers of 2004 and 2007. These surveys investigated RAC (residential air conditioner) usage patterns for cooling and indoor thermal environments in households over 20 years. The results showed that indoor temperatures have decreased over time, with air conditioners being operated at lower temperatures in 2024 than in previous years. Additionally, indoor temperatures remained more stable regardless of outdoor temperature. These findings suggest that cooling control behavior and thermal environment have changed over the years, likely influenced by technological advancements and personal preferences. This study provides insights into long-term trends in cooling behavior and indoor thermal environments, enhancing understanding of how occupants adjust cooling behavior as influenced by environmental and technological changes.

KEYWORDS

RAC; Thermal environment; Air-Conditioning Usage Behaviors; Indoor Environment Control; Cooling adaptation

1 INTRODUCTION

As the global climate continues to shift and average summer temperatures rise, the control behavior of cooling has changed significantly over the past two decades. In particular, the increasing frequency and severity of heat waves has led to a significant surge in electricity demand for cooling (Kim et al., 2022). With the advancement of cooling technologies, the penetration of cooling appliances in households, specifically air conditioners, has increased considerably over time. Globally, the average penetration rate of air conditioners increased from 20% in 2000 to 37% in 2022, while in Korea, it also climbed from 36% in 2001 to 97% in 2022 (IEA, 2023; Gallup 2018; Gallup 2023). The increased adoption of air conditioners is likely to have altered people's adaptation to indoor climates during the summer.

Building upon previous studies (Chun and Bae, 2005; Bae et al., 2008), this research investigates the indoor thermal environment and cooling control behavior in Korean households during the summers of 2004, 2007, and 2024, analyzing the long-term changes over time. By comparing these findings with previous data, this study seeks to provide insights into the changing air conditioning usage pattern, people's thermal adaptation, and contribute to predicting future energy consumption.

2 METHODS

This study investigated the indoor thermal environment in households across Seoul, Gyeonggi, and Incheon, South Korea, during the summers of 2004 (July 3– August 31), 2007 (August 24–

August 31), and 2024 (July 1– September 20). These metropolitan areas are all located in Seoul and its surrounding regions, within a one-hour travel distance, which has a mid-latitude temperate climate and a continental climate with notable seasonal temperature variations. Summers, in particular, are characterized by hot and humid weather.

As shown in Table 1, indoor temperature, relative humidity, and air-conditioner usage were measured in 29 households in 2024, and in 6 and 18 households in 2004 and 2007, respectively. All these households have at least one air conditioner, and the measurement location was limited to the living room, where air conditioners were generally installed in Korea.

This study aimed to analyze the differences in indoor thermal environments and air-conditioner usage behavior. In order to measure the indoor thermal environment, a temperature and humidity data logger was installed at 1.1 meters above the floor and away from direct airflow or other heat sources to record indoor temperature and relative humidity at each measurement interval (Table 1). The on/off events of AC were identified by analyzing changes of indoor air temperature (Jian et al, 2022) and temperature at the AC vent (Yan et al., 2021; Du and Pan, 2022). An additional data logger was installed at the AC vent to record the discharged air temperature at regular intervals. To identify the operational status of the AC, we defined abrupt drop as an “on” event and an abrupt increase as an “off” event.

Table 1. Overview of temperature and humidity measurement

City	Measurement period	Number of households	Instruments	Measurement interval
Seoul	2004.07.03–08.31	6	HOBO (Onset)	2min
Gyeonggi	2007.08.24–08.31	18	HOBO (Onset)	4min
Incheon	2024.07.01-09.20	29	Elitech Tlog10EH, Testo174T	10min

3 RESULTS

Although the study in 2007 was conducted a total of eight days, air conditioners were actually used in all households only during a five-day period from August 24 to 28. In this study, we primarily focused on comparing long-term data from July to August in 2004 and 2024. Due to its limited duration, the data of 2007 was not included in the seasonal analysis. Instead, it was analyzed separately under comparable outdoor conditions.

Changes in outdoor conditions and indoor temperature over time

A comparison was made for the same period (July 3 to August 31) between 2004 and 2024. Figure 1a shows the outdoor temperatures in 2004 and 2024, based on data measured by the Seoul Meteorological Administration. In 2004, the average outdoor temperature was 25.5°C, with a maximum of 29.1°C and a minimum of 22.6°C, and the average relative humidity was 75.7%. In 2024, the average outdoor temperature was 28.1°C, with a maximum of 31.6°C and a minimum of 25.3°C, and the average relative humidity was 76.8%.

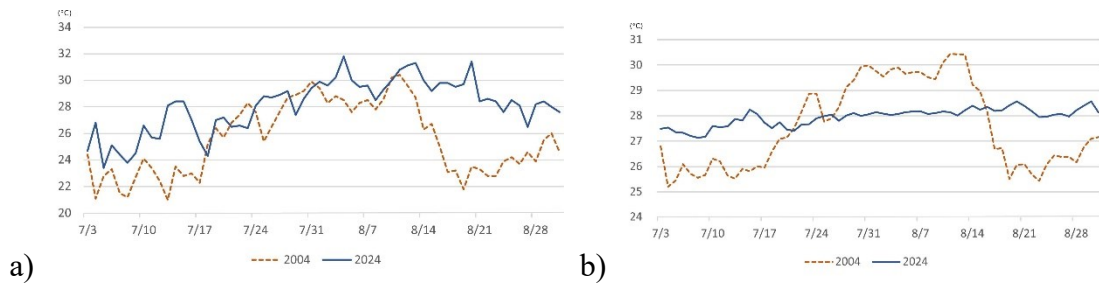


Figure 1. a) Outdoor average temperature and b) indoor average temperature in 2004 and 2024

Over the measurement period, the indoor temperature averaged 27.56°C (SD=1.71) in 2004, compared to 27.94°C (SD=0.35) in 2024. According to an independent samples t-test, there was no statistically significant difference. However, based on Levene's test the variance in indoor temperatures in 2024 was notably smaller ($p<0.001$).

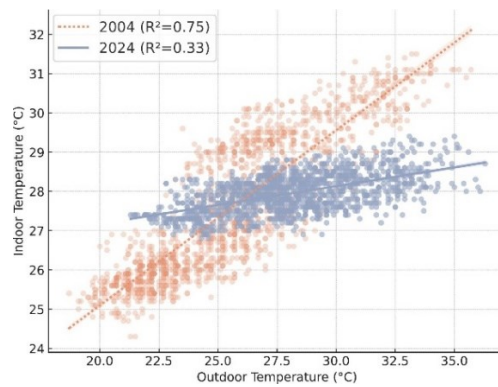


Figure 2. Linear regression analysis between outdoor and indoor temperature in 2004 and 2024

Given that the variance in indoor temperature was significantly lower in 2024, the relationship between outdoor and indoor temperatures was analyzed to investigate changes in AC usage patterns. Figure 1b shows that while average indoor temperatures in 2004 present considerable variability, those in 2024 tend to remain relatively stable. Since the daily average outdoor temperature has the strongest correlation with occupants' AC usage (Chun and Bae, 2005), this stability suggests a change in cooling behavior. According to a linear regression analysis of the relationship between outdoor and indoor temperature, in 2024 ($R^2=0.33$), the influence of outdoor temperature on indoor temperature has decreased compared to 2004 ($R^2=0.75$) (Figure 2). This suggests that, unlike two decades ago, as people have adapted to the use of air conditioning in the summer, an increasing number of occupants may be maintaining a constant set temperature due to changes in personal comfort preferences.

Indoor thermal environment under air conditioning control

When comparison of indoor temperatures at the activation and deactivation of AC showed that in 2004, it was turned on at an average indoor temperature of 30.26°C and turned off at 28.19°C. In 2024, it was turned on at 29.02°C and turned off at 26.99°C (Figure 3). According to an independent samples t-test, this difference was statistically significant ($p<0.001$), indicating that in 2024, the air conditioner was turned on at a temperature approximately 1.24°C lower and turned off at a temperature approximately 1.20°C lower than in 2004.

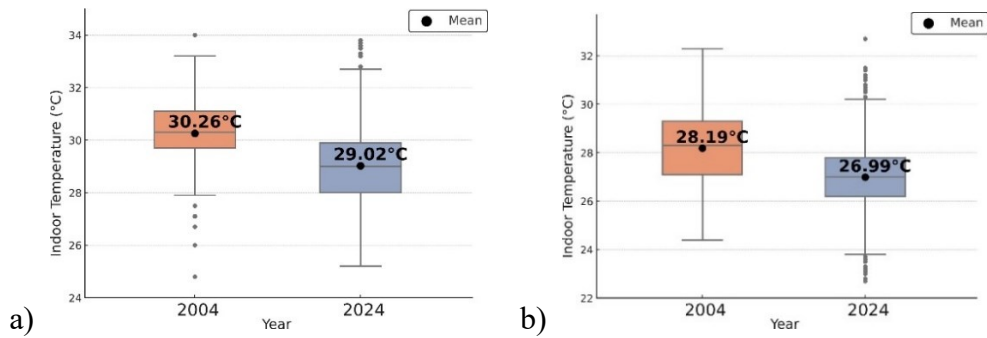


Figure 3. The average temperature a) when AC is on, and b) when AC is off

Analysis under similar outdoor conditions

Due to the lower outdoor summer temperatures in 2007, we extracted five days from the 2004 and 2024 data that showed outdoor temperatures of at least 26.3°C and below 28.7°C, consistent with the conditions in 2007. The data on outdoor conditions for five days in each year are presented in Table 2.

Table 2. Summary of five days' outdoor temperature by year (°C)

Selected period	Average	Minimum	Maximum
2004.08.04-08.08	28.1	24.8	32.6
2007.08.24-08.28	27.4	24.1	31.6
2024.08.24-08.28	27.8	24.6	31.6

As shown in Figure 4, the hourly average indoor temperature in 2024 was lower than in both 2004 and 2007. To examine the pattern of indoor temperature change, a linear mixed model was used. The results indicated that the hourly average indoor temperature in 2024 was significantly lower ($p < 0.001$).

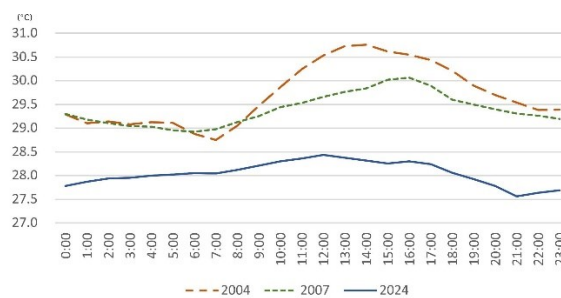


Figure 4. Hourly average indoor temperature in 2004, 2007, and 2024

A one-way ANOVA was conducted to compare the indoor thermal environment under AC control among 2004, 2007, and 2024. As shown in Table 3, when turning on the air conditioner, the average indoor temperatures were 30.92°C in 2004, 29.38°C in 2007, and 28.99°C in 2024, indicating that in 2024 the air conditioner was activated at a lower temperature. The difference among the three years was statistically significant ($p < 0.001$). When turning off the air conditioner, the average indoor temperatures were 28.80°C in 2004, 25.82°C in 2007, and 27.14°C in 2024. According to the result of ANOVA, these differences were also statistically significant ($p < 0.001$). Notably, the average indoor temperature in 2007 was 25.82°C (SD=1.30), which was lower than in 2024 (27.14°C, SD=1.09).

	2004	2007	2024
ON	30.92	29.38	28.99
OFF	28.80	25.82	27.14

4 DISCUSSION

Relationship between indoor and outdoor temperature

Extending the analysis beyond daily indoor temperature averages, the inclusion of 2007 data provides more detailed understanding of how indoor temperatures change throughout the day under similar outdoor conditions. As depicted in Figure 4, unlike in 2004 and 2007, the indoor temperature in 2024 remained relatively consistent throughout the day. A mixed-model analysis including interactions with outdoor temperature identified a significant three-way interaction among year, hour, and outdoor temperature ($p=0.045$), implying that the effect of outdoor temperature on indoor temperature has decreased over the years. In other words, in 2024, indoor temperature tended to be maintained regardless of changes in outdoor temperature compared to 2004 and 2007, indicating that occupants have adapted to lower indoor temperatures in summer and that their cooling control behaviors have changed over time accordingly.

Changes in cooling behavior over time

The measurement results indicate that control behaviors have changed over the past 20 years. As shown in Figure 5a, under similar outdoor temperature conditions, the average indoor temperature in 2024 is lower than in 2004 and 2007. In addition, unlike in 2004, occupants in 2024 tended to turn on the AC at a relatively lower temperature (Figure 3a). Maintaining lower indoor temperatures possibly reflects the shifts in occupants' active control of cooling and economic considerations as noted in a previous study (Chun and Bae, 2005). This suggests that changes in occupants' cooling control behaviors, along with advancements in cooling performance of AC, may have led to more effective cooling. Although the result of one-way ANOVA did not indicate any statistically significant differences, the average cooling capacity per square meter showed an increasing trend over time (Figure 5b). One possible explanation for this trend is the increased adoption of inverter-type air conditioners, which automatically optimize operation to improve efficiency.

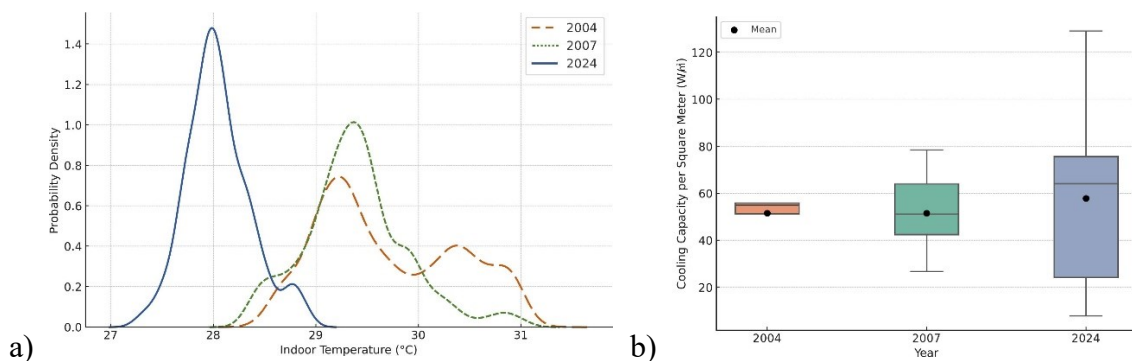


Figure 5. a) Probability Density Function of temperature and b) average cooling capacity per square meter by year

5 CONCLUSIONS

This research compared and analyzed changes in indoor thermal environments and occupants' RAC control behaviors in summer over the past 20 years (2004, 2007, and 2024). The results showed that occupants have increasingly tended to maintain lower indoor temperatures over the years. Specifically, in 2024, the temperature at which air conditioners were turned on was approximately 1.2°C lower than in previous years. Moreover, unlike in the past, indoor temperatures in 2024 remained more stable regardless of outdoor temperature fluctuations.

The tendency to maintain lower indoor temperatures may be attributed to human adaptation to lower indoor temperatures as a result of the widespread use of air conditioning. Traditionally, the use of RAC, unlike office air conditioning, is directly related to electricity costs and allows for greater control flexibility, leading to indoor temperatures that tend to be closer to outdoor temperatures. Nevertheless, humans, having adapted to air-conditioned environments over a long period, can be interpreted as maintaining lower indoor temperatures at home compared to 20 years ago.

6 ACKNOWLEDGEMENT

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7 REFERENCES

- Bae, C. H., Bae, N. R. and Chun, C. Y. 2008. Research on Indoor Thermal Environment and Residents' Control Behavior of Cooling according to Household Type in Apartment. *Journal of the Korean housing association*, 19(1), 89-96.
- Chun, C. Y. and Bae, N. R. 2005. A study on acceptable thermal comfort zone and resident behavior of operating cooling devices in apartments. *Korean Journal of Air-Conditioning and Refrigeration Engineering*, 17(5), 477-486.
- Du, J. and Pan, W. 2022. Cooling-related energy uses and adaptive behaviors in high-rise residential buildings in the subtropical climate: A case study in Hong Kong. *Building and Environment*, 223, 109456.
- Gallup. 2018. Air Conditioner Ownership, Usage Rate, Daily Usage Hours, Cooling Set Temperature, and Primary Brands (1993–2018), in *Gallup Korea Daily Opinion*, U.R. Air Conditioner Ownership, Daily Usage Hours, Cooling Set Temperature, and Primary Brands (1993–2018), Gallup.
- International Energy Agency. 2018. *The Future of Cooling*. IEA: Paris.
- Jian, Y., Liu, J., Pei, Z. and Chen, J. 2022. Occupants' tolerance of thermal discomfort before turning on air conditioning in summer and the effects of age and gender. *Journal of Building Engineering*, 50, 104099.
- Kim, Y., Choi, Y. and Min, S. K. 2022. Future changes in heat wave characteristics and their impacts on the electricity demand in South Korea. *Weather and Climate Extremes*, 37, 100485.
- Yan, S., Liu, N., Wang, W., Han, S. and Zhang, J. 2021. An adaptive predicted percentage dissatisfied model based on the air-conditioner turning-on behaviors in the residential buildings of China. *Building and Environment*, 191, 107571.