Research on occupant-centric HVAC control

A field study on the effects of introducing HVAC control that is responsive to occupants' thermal sensations

Mayumi Miura
Haruka Ueda
Ryota Dazai
Yuka Shimizu*
Toshiharu Ikaga**

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The control of heating, ventilation, and air-conditioning (HVAC) plays a large role in creating an indoor environment that contributes to office workers' well-being and high productivity. An occupant-centric HVAC control with a control loop directly connected to occupants' thermal sensation feedback has been proposed. We investigated the thermal sensations, thermal satisfaction, and subjective performance of office workers and the energy consumption of an office which employs the proposed control technology.

1. Introduction

Because we spend about 90 % of our life indoors according to reported data,[1] architectural spaces are closely related to our lives. Since the announcement in 2014 of WELL Building Standard™, an assessment system of built environment that focuses on peoples' health and well-being (physical, mental, and social wellness),[2] healthy and comfortable indoor environment can be assessed according to global standards. In addition, since the sustainable development goals (SDGs) adopted at a UN summit in 2015 placed importance on the promotion of inclusive and sustainable economic growth,[3] the improvement of workplace productivity is one of the most important factors in supporting sustainable economic development. In light of this background, there has been an international focus on real estate that fosters excellent worker's health and comfort in terms of the good quality of work environments and workplace productivity and of securing top-notch human resources. In Japan, the operation of CASBEE® (Comprehensive Assessment System for Built Environment Efficiency)-WO (Wellness Office) certification[4] began in 2019 as a certification system to encourage the spread of such buildings. CASBEE-WO assesses not only elements that directly affect the health and comfort of office workers in a building, but also factors that contribute to the improvement of workplace productivity.

HVAC control in buildings plays an important role in creating the above-mentioned healthy comfortable spaces that lead to high workplace productivity. ASHRAE, which is very influential in international standards and guidelines, has adopted indoor environmental quality (IEQ) as a strategic focus in its 2019–2024 strategic plan. A chapter titled "Occupant-Centric Sensing and Control" has also been added to the *ASHRAE Handbook*[5] to cover occupant-centric measurement and control.

Satisfaction with the indoor environment is said to have an effect on the improvement of performance,[6] therefore satisfaction with the HVAC control is an important element in achieving a high-quality indoor environment. However, thermal sensations (hot/cold feelings) and comfort differ depending on the occupant even within the same environment. Therefore, there is a limit on the degree to which occupants' environmental satisfaction can be improved by blanket HVAC control that sets the room temperature at a certain value.

For that reason a new HVAC control solution is proposed for raising level of occupants' environmental satisfaction. It allows occupants to freely vote, entering their own hot/cold thermal sensation feedback into the air conditioning control loop through a web browser screen or dedicated device.[7, 8] This HVAC control that is responsive to occupants' thermal sensations is also expected to improve the satisfaction of occupants by giving them the controllability of their environment,[9] providing a feeling of self-efficacy.*1

In our research, we conducted a field study to examine how the introduction of the new HVAC control that is responsive to occupants' thermal sensations affects the thermal satisfaction and workplace productivity in an open-plan office where many people work. We also investigated the indoor environment and HVAC energy consumption before and after the introduction of the new HVAC control.

This article describes differences between conventional HVAC control with constant room temperature and the new HVAC control that is responsive to occupants' thermal sensations in section

* Master's Program, Graduate School of Science and Technology, Keio University
** Professor, Ph.D. in Engineering, Faculty of Science and Technology, Keio University

*1 An individual's beliefs in their capacity to achieve

2, provides an overview of the actual office study in section 3, and presents the study and analysis results in section 4.

2. Conventional HVAC control with constant room temperature vs. new HVAC control that is responsive to occupants' thermal sensations

2.1 Conventional HVAC control with constant room temperature

Figure 1 illustrates a conventional HVAC control loop where the facility manager (or the operator) determines a certain room temperature set point. The facility manager sets the set point at which occupants should feel comfortable, considering factors such as the manager's personal experience, the indoor temperature range according to government requirements,*2 and the predicted mean vote (PMV), which is a comfort index used in the ISO 7730 and ANSI/ASHRAE standards. The HVAC system controls the room temperature so that it reaches the set point. However, how the occupants feel may be different from the "standard" feeling and each occupant feels different. As a result, the room temperature is often different from the temperature at which occupants actually feel comfortable.

2.2 New HVAC control that is responsive to occupants' thermal sensations

Figure 2 illustrates a control loop for HVAC control that is responsive to occupants' thermal sensations. Thermal sensations are sent directly from occupants and act as feedback for the HVAC control loop. With HVAC control that is responsive to occupants' thermal sensations, the temperature set point is corrected according to thermal sensation feedback from the occupants themselves, although the facility manager determines the initial temperature set point as in figure 1. This configuration for using information from occupants as feedback for the HVAC control loop also matches the above-mentioned ASHRAE Occupant-Centric Sensing and Control scheme.

The room temperature set point is corrected according to received information. For example, when the system receives a "Cold" vote from an occupant, it raises the set point by 0.5 °C. When it receives a "Hot" vote, it lowers the set point by 0.5 °C. Figure 3 shows conceptual graphs of the room temperature set points in figures 1 and 2.

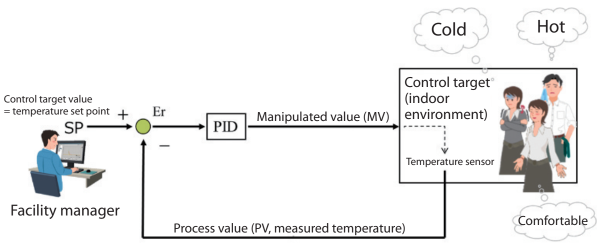


Fig. 1. Example of an HVAC control loop where the facility manager determines the temperature set point

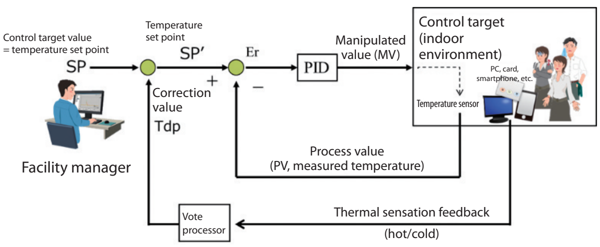


Fig. 2. Example of an HVAC control loop that is responsive to occupants' thermal sensations

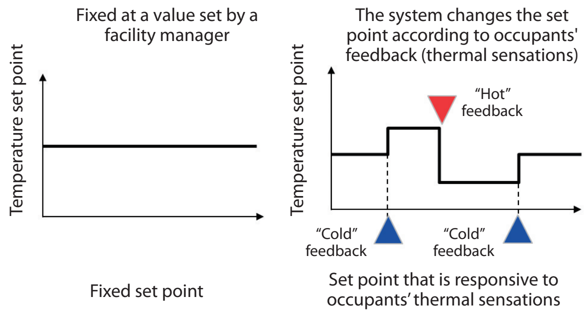


Fig. 3. Conceptual graphs of the room temperature set point

3. Field study of an office with HVAC control that is responsive to occupants' thermal sensations

This section provides information of the conducted field study.

3.1 Overview

We investigated an office area in an administration building of A. Co. (3rd floor, 298 workers) in the summer of 2019. Table 1 gives an overview of the study. The room temperature set point was controlled with the fixed value from July 23 to July 31. Then, after the introduction of the new HVAC control, the room temperature set point was changed according to thermal sensation feedback from August 1 to August 8. Hereafter, these periods are referred to as "before installation" and "after installation" respectively. In addition, we measured the actual office environment and conducted web questionnaire surveys of the office workers. HVAC operation data (such as the room temperature set point) during the whole periods was periodically collected by the HVAC system.

3.2 The office area and HVAC control

3.2.1 HVAC zoning

The HVAC zones in the office area are shown in figure 4. The office area is broken down into eight interior zones (SI zones) and eight perimeter zones (SP zones) from east to west, and used variable air volume (VAV) central air conditioning system with an air handling unit (AHU). Fig. 5 is a photo of an interior zone. (The photograph was taken from the position indicated by the arrow at the right in figure 4.) There are only a few desks in the SP zones; most workers are at desks in the SI zones.

3.2.2 HVAC control

The installed HVAC control[8] raises the temperature set point by 0.5 °C when it receives a "Cold" vote and lowers the set point by 0.5 °C when it receives a "Hot" vote. More specifically, the set point stays 2.5 °C lower for 10 minutes after a "Hot" vote is received and then it changes to the actual corrected value, which is lower than the original set point by 0.5 °C. This method improves the responsiveness of HVAC control to thermal sensation votes so that occupants are more likely to feel changes in the environment. Workers sent thermal sensation votes from the browser screen on their PCs (Fig. 6) by selecting the name of the HVAC zone where their desk is located and then selecting their thermal sensation from among Hot, Good, and Cold.

*2 The Act on Maintenance of Sanitation in Buildings (the requirement of architecture in Japan).

3.3 Physical measurements

The measurement points in the office area are shown by the circled numbers in figure 4. We consecutively measured air temperature, relative humidity, globe temperature,*3 and illuminance every 10 minutes and air velocity every 5 minutes at the 12 measurement points on the floor. In addition, we consecutively measured CO_2 concentration every minute for one hour on a typical day.

Table 1. Field study overview

	Before installation	After installation
Period	July 23–31, 2019	Aug. 1–8, 2019
Building	A. Co. admin. building, 3rd floor	
HVAC system	VAV central air-conditioning system	
Number of office workers	298 (male: 196, female: 102)	
Measurements	- Physical Measurements at 12 locations Air Temperature, relative humidity, air velocity, illuminance, CO_2 concentration - Psychological measurement (Survey by Web questionnaire) Individual attributes (once before installation) Subjective assessment (once before installation and once after installation)	
Questionnaire response period	July 23–25	August 7–8

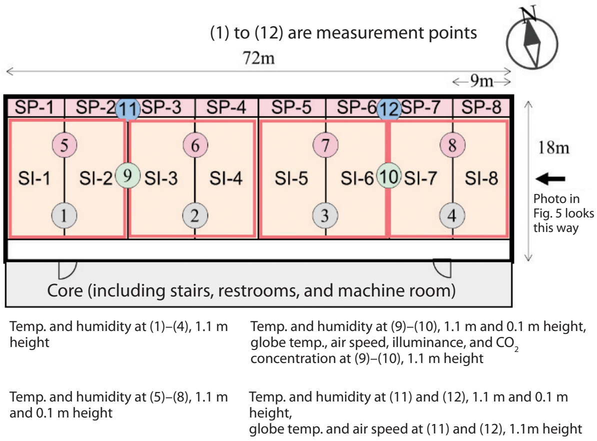


Fig. 4. HVAC zones and physical measurement points

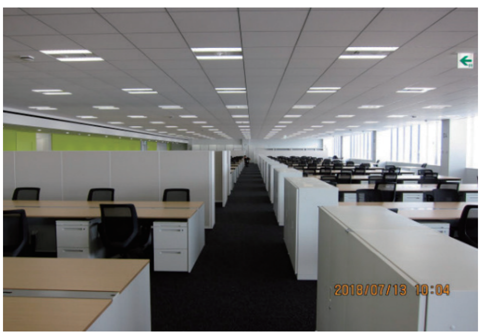


Fig. 5. Photograph of the office space

*3 Also called black bulb temperature. Indoors, it is measured to observe the effects of radiant heat from the surroundings, such as walls and windows.

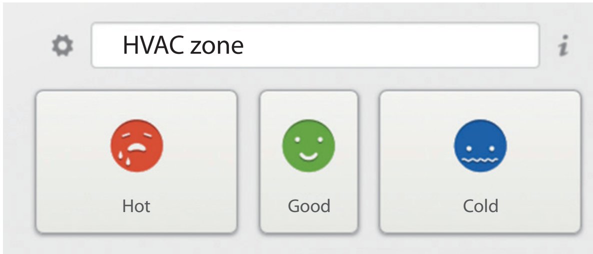


Fig. 6. Screen on which workers submit thermal sensation votes

3.4 Psychological measurements

All surveys were conducted by Web questionnaire. A questionnaire before installation included items about individual attributes such as gender, age group, BMI,*4 sensitivity to hot and cold environment (whether more sensitive than the average person), and seat occupancy rate. In addition, we conducted a survey by questionnaire once before and once after installation to assess psychological quantity such as thermal sensation and thermal satisfaction as well as subjective work efficiency*5 (table 2).

4. Measurement results

This section reports the results of the measurements described in section 3. The indoor environment evaluation described in section 4.1 is discussed in units of the four areas in the red frames in figure 4 (SI-1 and SI-2, SI-3 and SI-4, SI-5 and SI-6, and SI-7 and SI-8 that correspond to the environmental measurement points (1)-(8) in figure 4.

4.1 Indoor environment evaluation

4.1.1 Results of physical measurement

Table 3 shows the results from measuring the indoor environment before and after installing the HVAC control that is responsive to occupants' thermal sensations (the average value and standard deviation of the environmental measurements taken at the points on the floor during working hours in each period). Although CO_2 concentration data before installation is missing, we confirmed that the CO_2 concentration in the indoor return air collected in the HVAC system did not greatly change through the whole period of this study. Therefore, it can be assumed that the illuminance and CO_2 concentration were almost the same level before and after installation. The air temperature rose by 0.4 °C and the PMV,*6 which indicates average thermal sensation, rose by 0.2 after installation. This indicates that the indoor environment shifted to warmer after installation. The PMV rose from a range of −0.1–0.0 before installation to a range of 0.1–0.2 after installation. A change of about +0.2 in each area was with little variation between areas. Here, of the four physical quantities used in calculating the PMV (air temperature, globe temperature, relative humidity, and air velocity)*7 in table 3, the air velocity and relative humidity were almost equal before and after installation or had shifted to the cooler side after installation, which reduced the PMV. This means that the PMV rose due to a rise in air temperature and globe temperature (physical

*4 Body mass index, an indication of the degree of obesity.

*5 The number of respondents is 179 for the questionnaire before installation and 127 for the questionnaire after installation. Both questionnaires were answered by 89 people. We used the data from 87 respondents (excluding whose physical conditions were bad) as a sample of those who answered both questionnaires.

*6 PMV is an international standard thermal comfort index as described in section 2.1. PMV is defined in the range of −3 to +3. PMV = 0 indicates a thermally neutral condition (comfort condition from an engineering standpoint) where you neither feel hot nor cold. A negative value indicates a thermal sensation on the cold side and a positive value indicates a thermal sensation on the hot side (−3: "Very cold" and +3: "Very hot"). The comfort range is −0.5 ≤ PMV ≤ +0.5 (Recommended range of ISO7730).

quantities related to the radiant heat environment). Because the PMV is an international standard and average index that assumes thermal sensation of a large number of people, it may often be different from the thermal neutral point and comfort range of actual office workers.[10] Therefore, if the air temperature rose after installation in response to thermal sensation votes from workers, we can conclude that the indoor environment was adjusted as they preferred. Responses to thermal sensation votes are accumulated in the HVAC system as temperature set point change history. Analysis of the room temperature set point is discussed in the next section.

Table 2. Items of psychological measurement

Item	Assessment scale
Physical condition	1(Bad) - 5(Good)
Air temperature	1(Cold) - 7(Hot)
Humidity	1(Dry) - 5(Humid)
Airflow	1(Very uncomfortable) - 7(Very comfortable)
Vertical difference of temperature	1(Feel strongly) - 4(Do not feel at all)
Thermal satisfaction	1(Satisfied) - 5(Dissatisfied)
Air quality satisfaction	1(Satisfied) - 5(Dissatisfied)
Subjective work efficiency	0 to 100 % (100 % the highest work efficiency)

Table 3. Result of physical measurements of indoor environment (average value ± standard deviation across the floor)

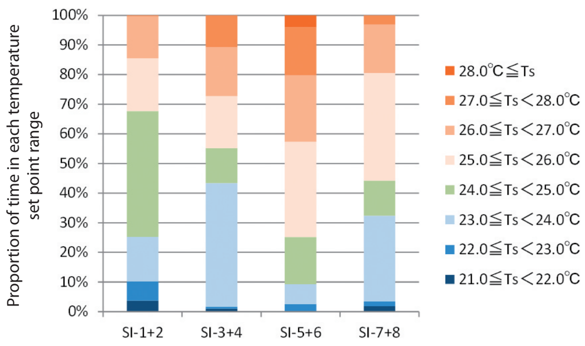
	Measurement height	Before installation	After installation
Air temperature [°C]	1.1 m	24.7 ± 0.7	25.1 ± 0.6
	0.1 m	24.5 ± 0.4	24.9 ± 0.6
Globe temperature [°C]	1.1 m	24.5 ± 0.3	25.1 ± 0.7
Relative humidity [%]	1.1 m	51 ± 7	47 ± 5
Air velocity [m/s]	1.1 m	0.11 ± 0.06	0.15 ± 0.15
PMV	1.1 m	−0.1 ± 0.2	0.1 ± 0.3
CO_2 concentration [ppm]	1.1 m	—	813 ± 45
Illuminance [lx]	1.1 m	929 ± 88	918 ± 110

4.1.2 Analysis of room temperature set point and air temperature

To confirm that the rise in PMV shown in section 4.1.1 was based on thermal sensation votes from workers, we analyzed the room temperature set point data collected by the HVAC system every minute. Whereas the room temperature set point was fixed at a certain value before installation, the set point changed in line with thermal sensation votes from workers after installation, as described in 2.2. Figure 7 shows the proportion of time of each room temperature set point range after installation (during working hours in the period). The room temperature set point was 26.0 °C in SI-1 and 24.0 °C in SI-2–SI-8 before installation. Therefore, the proportion of time of each room temperature set point range in each area was as follows before installation: 24.0 °C, 26.0 °C accounted for 50 %, 50% respectively in area SI-1+2, and 24.0 °C accounted for 100 % in the other three areas (not shown in the figure). In contrast, it can be seen that the set point in the various areas broadened to a range of 21.0–28.0 °C in response to thermal sensation votes from workers after installation. In areas SI-1+2, time slots for temperatures lower than 25.0 °C accounted for 68 %, which indicates that the set point shifted to the cooler side on average compared with the situation before installation. However, time slots of 24.0 °C or higher accounted for 90 % and 68 % in areas SI-5+6 and SI-7+8 respectively, which indicates that the set point shifted to the warmer side. In area SI-3+4, the set point broadened to both sides.

The set point changed little before and after installation in the perimeter zones, probably because only a small number of workers work there. The total across the floor including the perimeter zones shows that the time slots for 25.0 °C or higher increased by 36 % while those lower than 24.0 °C increased by 14 %. In other words, the set point rose in response to thermal sensation votes from workers on the floor as a whole. Because the workers send their thermal sensation votes while also feeling the effect of the radiant environment (rise in globe temperature) described in 4.1.1, it can be concluded that the set point rose as a result of environmental adjustment by workers. Also, if we look at the changes in air temperature in each area shown in figure 8, we see that it became lower in SI-1+2, where the average set point shifted to the cooler side, but rose in the other areas.

The next section shows the results of the assessment on how this environment adjustment changed the thermal sensation, thermal satisfaction, and workplace productivity of workers.



*The room temperature can be set in 0.5 °C increments.

Fig. 7. Proportion of time of each room temperature set point range (after installation)

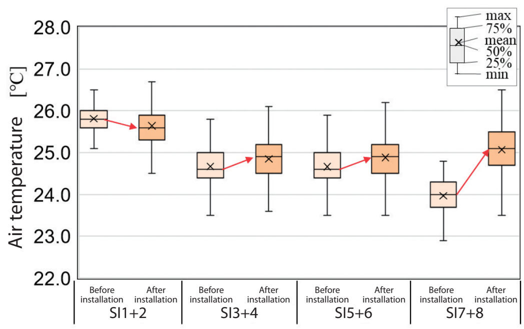


Fig. 8. Changes in air temperature (1.1 m above the floor)

*7 Four physical quantities (air temperature, mean radiant temperature, relative humidity, and air velocity) and two people-related quantities (clothing and metabolic rate) are used to calculate the PMV. The changes in the PMV in table 3 are mainly caused by changes in the four physical quantities because constant values (assuming an office in summer) were used for the clothing and the metabolic rate (clothing: 0.6 clo, metabolic rate: 1.2 MET) during calculation of the PMV. In addition, mean radiant temperature is the physical amount that indicates the radiant heat environment and can be calculated from the globe temperature and air velocity in table 3.

4.2 Assessment of thermal sensation, thermal satisfaction, and workplace productivity

We compared the thermal sensations, thermal satisfaction, and workplace productivity (subjective work efficiency) before and after the introduction of TSF control using the results of questionnaire responses. The results as a whole are assessed in 4.2.1. In section 4.2.2 they are assessed after dividing the respondents into those who submitted thermal sensation votes and those who did not, focusing on the differences between the two groups.

4.2.1 Comparison of before and after installation

(1) Assessment of thermal sensations

Figure 9 shows responses about thermal sensations before and after installation.*8 Responses on the hot side ("Warm" and "Hot") and cold side ("Cool" and "Cold") decreased after installation and those in the neutral range ("Slightly Cool," "Neutral," and "Slightly Warm") significantly increased by 19.5 percentage points. Although table 3 shows that the average PMV during the period rose after installation, responses on the hot side ("Warm" and "Hot") decreased after installation. Because table 3 also shows that the air velocity increased and the standard deviation increased after installation, the heat may have been alleviated within the predetermined period while the HVAC control was responding to "Hot" votes (time slots when the set point was lowered and the air speed rose).

(2) Assessment of thermal satisfaction

Figure 10 shows responses about thermal satisfaction before and after installation.*8 Responses on the dissatisfaction side ("Slightly dissatisfied" and "Dissatisfied") decreased after installation and those on the satisfaction side ("Satisfied," "Slightly satisfied," and "Neutral") significantly increased by 9.3 percentage points. This improvement in thermal satisfaction is also consistent with the increase in responses about thermal sensation in the neutral range (Fig. 9).

(3) Assessment of subjective work efficiency

Figure 11 shows responses about subjective work efficiency before and after installation.*9 The subjective work efficiency significantly increased by 2.5 points after installation. It is presumed that an increase in thermal satisfaction as a result of the introduction of the HVAC control that is responsive to occupants' thermal sensations led to the increase in subjective work efficiency.

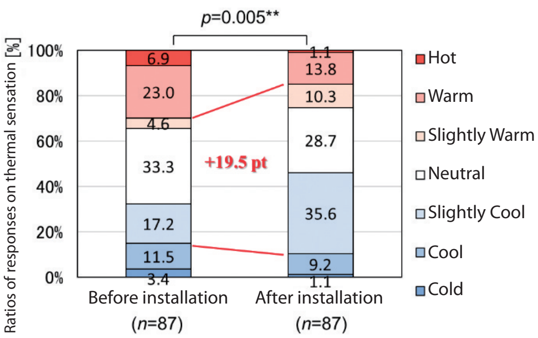


Fig. 9. Assessment of thermal sensation

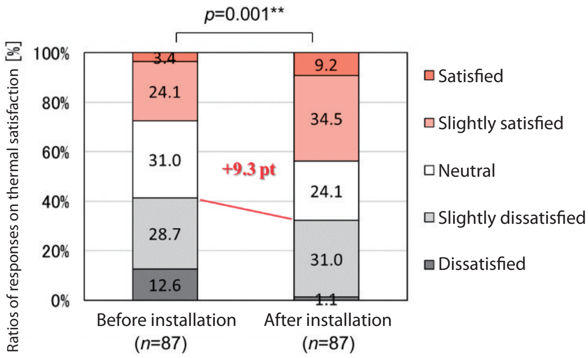


Fig. 10. Assessment of thermal satisfaction

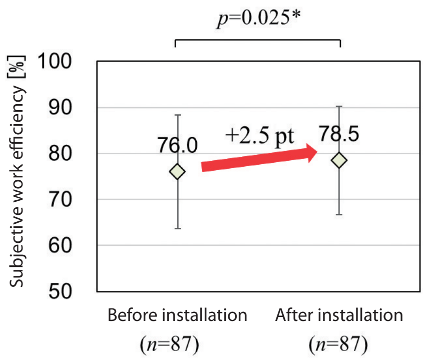


Fig. 11. Assessment of workplace productivity

4.2.2 Analysis of how voting action affects the comparison on thermal sensation, thermal satisfaction, and workplace productivity

It is reported that people feel more satisfied when making adjustments by themselves even if the environment is the same.[11] As described in section 1, HVAC control that is responsive to occupants' thermal sensations gives occupants the ability to change their environment. Therefore, even workers who do not actually made a thermal sensation feedback of their own will may be more likely to accept the environment and feel a higher level of thermal satisfaction. In this section, we divide the workers into those who submitted their thermal sensations and those who did not (hereafter, feedback group (FB Gr) and no-feedback group (no-FB Gr)) and compare the results of their reported thermal sensations, thermal satisfaction, and workplace productivity.*10

(1) Assessment of thermal sensation

Figure 12 compares the responses of FB and no-FB Gr about thermal sensations before and after installation.*11 The responses in the moderate range ("Slightly Cool," "Neutral," and "Slightly Warm") significantly increased by 20.8 points after installation in the group of workers who did not vote. In addition, the "Hot" and "Warm" responses decreased and the "Slightly Cool" responses increased after installation in both groups. No-FB Gr may also have felt that the heat was alleviated within the predetermined period while the HVAC control responded to the "hot" votes from FB Gr.

(2) Assessment of thermal satisfaction

Figure 13 compares the responses of FB and no-FB Gr about thermal satisfaction before and after installation.*11 After installation, responses about thermal satisfaction on the satisfaction side

*8 We used the Wilcoxon signed-rank test (†: $p < 0.10$, *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$).

*9 We used the paired t-test (†: $p < 0.10$, *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$).

*10 We used the data from 87 of the 89 respondents who answered questionnaires both before and after installation (excluding those whose physical conditions were bad) as samples for the analysis of FB and no-FB Gr.

*11 We used the Wilcoxon signed-rank test and the Mann–Whitney U test before and after installation (†: $p < 0.10$, *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$).

("Satisfied," "Slightly satisfied," and "Neutral") significantly increased by 4.5 points among FB Gr and by 14.0 points among no-FB Gr. Presumably FB Gr were more satisfied because of the HVAC operation in response to their voting actions and the feeling of control. Regarding no-FB Gr, open responses in the questionnaire (about why they did not vote) and other data suggest that a certain portion of workers who felt uncomfortable but did not bother to vote or did not vote for some other reason felt satisfied with changes in the thermal environment in response to others' votes.*12

(3) Assessment of subjective work efficiency

Figure 14 compares FB and no-FB Gr responses about subjective work efficiency before and after installation.*13 The subjective work efficiency increased in both groups. However, a significant difference is not observed in no-FB Gr, while the subjective work efficiency of FB Gr increased significantly by 3.2 points.

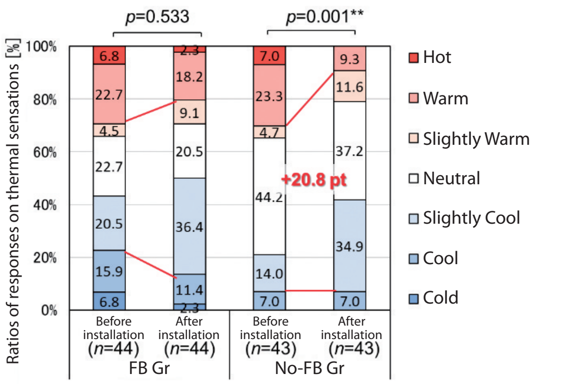


Fig. 12. Assessment of thermal sensations (FB and no-FB Gr)

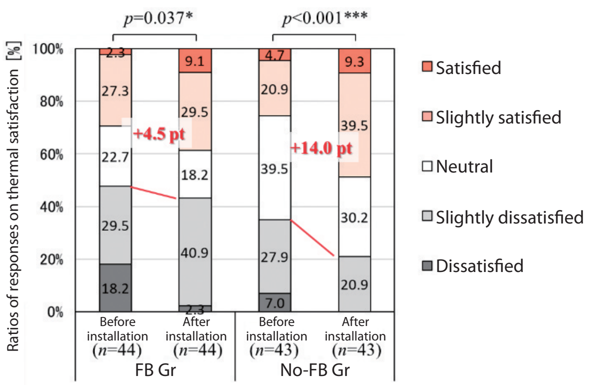


Fig. 13. Assessment of thermal satisfaction (FB and no-FB Gr)

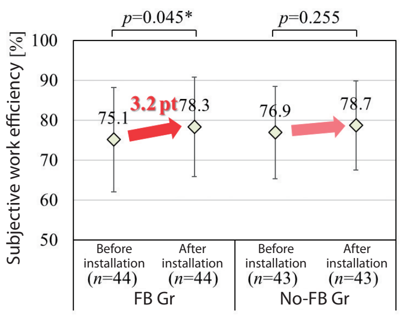


Fig. 14. Assessment of workplace productivity (FB and no-FB Gr)

*12 More than half of the workers who answered that they did not vote (because it was a bother, or they left the decision to others, or they were trying to consider how others' felt, and for other reasons) selected a response on the questionnaire on the satisfaction side about thermal satisfaction after installation.

*13 We used the paired t-test (†: $p < 0.10$, *: $p < 0.05$).

4.2.3 Energy assessment

Figure 15 shows the relationship between the outdoor air enthalpy and the daily total energy (of air conditioning) during working hours. Both the outdoor air enthalpy and the total energy were larger after installation compared with before installation. This section shows the result of assessment for two days before installation and six days after installation (in the blue frame in the figure), when outdoor air enthalpy was high.

(1) Energy consumption

Figure 16 shows the daily average energy consumption of the central plant and AHU before and after installation. The energy consumption of the central plant (chiller) decreased by 6 % but the energy consumption of the AHU (supply and exhaust fans) increased by 8 % compared with before installation. The total energy consumption of the central plant and AHU decreased by 3 % after installation.

(2) Analysis of supply air temperature, supply airflow, and energy consumption

The supply air temperature rose to 17.3 ± 1.8 °C after installation from 15.8 ± 1.0 °C (average value ± standard deviation) before installation. This is probably because the set point rose and the supply air temperature rose as a result of the introduction of the HVAC control that is responsive to occupants' thermal sensations. On the other hand, the total volume of supply air across the floor remained unchanged but the standard deviation of the VAV airflow rates across the floor increased by about 2.8 times compared with before installation. Table 3 shows that the air velocity and its standard deviation increased after installation. Presumably the power use by fans increased because the VAV airflow rate changed, and the inverter output for the supply and exhaust fans increased to maintain air balance in line with changes in the set point in response to thermal sensation votes from occupants.

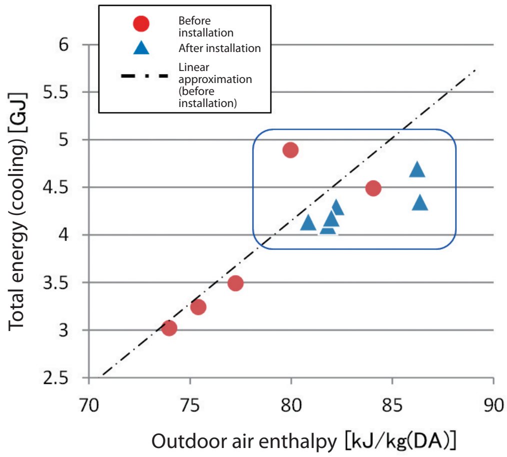


Fig. 15. Outdoor air enthalpy and total energy

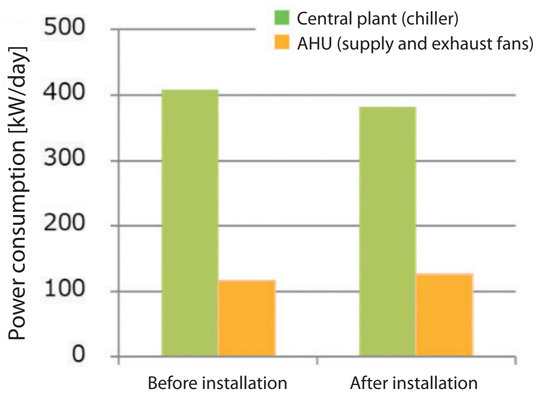


Fig. 16. Energy consumption

5. Summary

We investigated how the introduction of the HVAC control that is responsive to occupants' thermal sensations, in which room temperature set point changes in response to thermal sensation votes, affects the indoor environment, thermal satisfaction, and workplace productivity, as well as the energy consumption of the HVAC system. The findings of this field study on an office in the summer are as follows.

- The room temperature set point rose and the indoor environment (PMV) shifted to the warmer side across the floor in response to thermal sensation feedback from workers.
- Workers who felt "Hot," "Warm," "Cold," or "Cool" decreased as sensations shifted toward the neutral range. The indoor environment shifted to the warmer side on average. The heat may have been alleviated within the predetermined control period while the HVAC control responded to "hot" votes.
- The thermal satisfaction and subjective work efficiency of workers significantly increased.
- Separate analysis of the group of workers who submitted thermal sensation votes and those who did not shows that in both groups the thermal sensations shifted toward the neutral range and thermal satisfaction increased. There is a possibility that workplace productivity also increased in both groups.
- Energy consumption was reduced by 3 %. The energy consumption of the central plant decreased, mainly because the supply air temperature rose due to the rise in the set point.

These findings suggest that the introduction of HVAC control that is responsive to occupants' thermal sensation feedback contributes to the improvement of thermal satisfaction and workplace productivity of many workers.

6. Conclusions

For the technological development and improvement of occupant-centered HVAC control, research in various buildings where occupants are actually active is important. We will continue field study to develop technology for HVAC control that takes each occupant into account and achieves a high level of healthy and comfort indoor environment.

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Authors

Mayumi Miura — Product Development Department, Technology Development Headquarters, Azbil Corporation

Haruka Ueda — Product Development Department, Technology Development Headquarters, Azbil Corporation

Ryota Dazai — IB System Department, Marketing Headquarters, Building Systems Company, Azbil Corporation

Yuka Shimizu — Master's Program, Graduate School of Science and Technology, Keio University

Toshiharu Ikaga — Professor, Ph.D. in Engineering, Faculty of Science and Technology, Keio University