Article

Study on Winter Comfort Temperature in Mixed Mode and HVAC Office Buildings in Japan

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Abstract: Comfort temperature is important to investigate because the chosen office indoor temperatures affect the energy used in a building, and a thermally comfortable environment makes the occupants be more productive. The effects of temperature on comfort are broadly recognized for thermal comfort. Japanese office buildings are well equipped with air-conditioning systems to improve the thermal comfort of the occupants. The main objectives of this research were to compare the winter comfort temperature in mixed mode (MM) and heating, ventilation and air-conditioning (HVAC) office buildings and to investigate the relationship between the comfort temperature and the indoor air temperature. This study measured the thermal environmental conditions of the office buildings and surveyed the thermal comfort of the occupants. The field survey was conducted during winter in seven office buildings located in the Aichi prefecture of Japan. In total, 4466 subjective votes were collected from 46 occupants. The result suggested that the occupants were found to be more satisfied with the thermal environment of MM buildings than that of HVAC office buildings. Overall, 95% of comfort temperatures were in the range 22~28 °C in MM and HVAC buildings, which were higher than the indoor temperature of 20 °C recommended by the Japanese government. The comfort temperature was highly correlated to the indoor air temperature of the MM buildings than to that of HVAC buildings. This indicated that the occupants were more adapted towards the given thermal environment of MM buildings.

Keywords: field survey; office buildings; mixed mode; HVAC; thermal sensation vote; indoor air temperature; Griffiths' method; comfort temperature

1. Introduction

1.1. Overview

Today, people spend most of their time in an indoor environment. According to the survey conducted by the University of Maryland in early nineties, people spend 87% of their time inside buildings [1]. The occupants expect a level of thermal comfort that ensures comfort as well as wellbeing. Due to this reason, it is necessary that the conditions inside these office buildings remain thermally comfortable. Even gentle fluctuations in the indoor environment can cause discomfort, which may lead to a sudden change in the behavior or the activity of the occupants [2]. Temperature drifts with ±1 K of the customary temperature would attract little notice; ±2 K could cause mild discomfort among a small proportion of the occupants [3]. The adaptive principle states that "if change occurs so as to produce discomfort, occupants react in ways which tend to restore their comfort" [2]. Office workers use a variety of "adaptive opportunities" to regulate their indoor thermal environment and secure their thermal comfort [4]. It is important to adjust the indoor environment of the office with natural ventilation by opening the windows even when the air-conditioning (AC) is being used because many HVAC systems recycle the air from room to room increasing the risk of pathogens indoor [5–8] and in consideration of energy saving. Field surveys especially in naturally ventilated (NV), mixed mode (MM) and heating, ventilation, and air conditioning (HVAC) buildings around the world consider the comfort temperature. Indoor thermal environments can significantly influence human health and comfort as well as the energy consumption in the buildings.

The adaptive thermal comfort model is established around the world as ASHRAE standard 55 [9] and for European countries as European Standard EN 15251 [10]. The ASHRAE standard has accumulated a thermal comfort database for the naturally ventilated office buildings by defining an indoor thermal environment from field studies from across the world in different seasons [11], whereas the CEN standard [10] has accumulated a thermal comfort database from 26 office buildings from five European countries [12]. The major aim of these models is to define thermal comfort [3]. However, these standards do not include data from Japanese office buildings. This has overshadowed the understanding of the comfort temperature for Japanese office buildings. Japanese office buildings are well equipped with AC systems for maintaining indoor thermal comfort. Japanese government introduced the "Warm Biz" programs in the year 2005, where occupants were free to wear flexible clothing in winter, which recommend an indoor temperature of 20 °C for heating to ensure energy saving [13]. However, this value was not based on a field survey and lacked supporting evidence from a large database. Moreover, the adjustment of the indoor temperature by changing the clothing level may not give any assurance on whether the occupants are able to achieve the target of improving thermal comfort and reducing energy consumption [14], because any discomfort acquired by the occupants leads to behavioral changes to make themselves comfortable [15].

1.2. Previous Studies in Japanese Office Buildings

Comfort temperatures are important to investigate because the chosen office indoor temperatures affect the energy consumption in the building, and people in thermally comfortable environment are generally more productive. Based on field surveys, the comfort temperatures in Japanese offices was investigated by several researchers as shown in Table 1 [14,16–22]. The comfort temperature was found to be 25.0 °C, 25.4 °C and 24.3 °C for free-running mode (FR), cooling mode (CL) and heating mode (HT), respectively in the Kanto area of Japan [21]. Khadka et al. [22] found that the mean comfort temperature was 24.8 °C for MM and 25.0 °C for FR in Japanese office buildings. Tanabe et al. [23] found the comfort temperature was below 27 °C. These research works were mostly focused on the summer season or year-round and did not analyze the comfort temperature in detail for the winter season in MM and HVAC office buildings due to insufficient data or data collected for short periods of time. Shahzad and Rijal [24] found that MM offices had a higher level of occupants' comfort and satisfaction, while they also had the potential for low-energy

use. Thus, it is necessary to pay attention to understanding the comfort temperature in the winter season in these buildings.

Table 1. Literature review of comfort temperature in Japanese office buildings.

References	Area	Number of Buildings	Mode of Operation	Seasons	Number of Votes	Index Temperature (°C)	Comfort Temperature (°C)	Method
Nakano et al. [16]	Tokyo	1	HVAC	Four seasons	406	T_{op}	Male = 22.9 Female = 25.1	Regression
Tanabe et al. [17]	Tokyo	5	AC mode	Summer	1340	T_a	26.3	Regression
Indraganti et al. [18]	Tokyo	4	MM	Summer	2402	T_g	FR = 25.8 CL = 27.2	Griffiths
Mustapa et al. [19]	Fukuoka	2	Split-type AC system	Summer	401	T_g	26.6	Griffiths
Damiati et al. [20]	Yokohama Tokyo	3 1	MM	Autumn	173 282	T_{op}	25.8	Griffiths
Takasu et al. [14]	Tokyo and Kanagawa	5	MM	All seasons	2722	T_{op}	23.5 to 25.8	Griffiths
Rijal et al. [21]	Tokyo and Yokohama	11	HVAC MM	Summer/winter	4660	T_g	FR = 25.7 CL = 25.5 HT = 24.3	Griffiths
Khadka et al. [22]	Tokyo, Yokohama, Odawara	17	MM	All seasons	3000	T_g	MM = 22–26 FR = 23–25	Regression

T_{op}: operative temperature (°C), T_g: indoor globe temperature (°C), T_a: indoor air temperature (°C) FR: free-running mode, CL: cooling mode, HT: heating mode.

1.3. Objectives

The main objectives of this research were to compare the comfort temperature in MM and HVAC buildings in winter and to investigate the relationship between the comfort temperature and the indoor air temperature. The findings could be used to create guidelines and standards for cold climatic conditions facilitating the design of MM and HVAC buildings in the future. This understanding can also help to decrease the temperature setting for heating of existing buildings during the winter season to realize energy savings in the buildings.

2. Methodology

The field study focused on the environmental conditions of office buildings, the occupants' characteristics, thermal measurements and subjective questionnaires of thermal comfort. Figure 1 shows the flowchart of this study. We created this flowchart by referring to previous studies [25,26]. The data collection, data entry and data analysis are explained in the flowchart. We used the same research methodology for the Kanto region of Japan [15,21].

2.1. Study Area and Investigated Buildings

The study area was located in the Aichi prefecture of Japan (Figure 2). The location features a humid subtropical climate (Köppen climate classification: Cfa), which is characterized by hot and humid summer and cool winter. Figure 3 indicates the monthly mean outdoor air temperature and relative humidity of Nagoya's meteorological station. The chosen office buildings were 4.8 to 22 km away from the Nagoya meteorological station. Moreover, the microclimatic conditions of the investigated buildings were similar to those at the meteorological station. The average annual temperature in Nagoya reaches 15.5 °C. The temperatures are highest on average in August, at around 27.8 °C, and lowest in January, at around 4.1 °C, as shown in Figure 3. The average relative humidity varies from 60 to 77% in different months of the year.

1) Field survey planning

2) Data collection

A. Conducting field survey (office buildings)

B. Obtaining outdoor data from Japan meteorological station

(a) Subjective data

- Thermal sensation vote (TSV)

(b) Indoor field measurement

- Air temperature
- Relative humidity

- Air temperature
- Relative humidity

3) Data entry

Integrating to indoor data

Objective database (indoor and outdoor)

Integrating to subjective database

Database (subjective and objective)

4) Data analysis

- Statistical analysis using SPSS and Excel

A. Experimental condition and subjective data

- Outdoor and indoor air temperature

B. Calculating comfort temperature

- Regression method
- Griffiths' method

C. Relation between comfort temperature and indoor air temperature

Figure 1. Flowchart of this study.

Aichi

N 1, N2, N3, N4, N 5, N6, N7

Nagoya

Hokkaido

Aichi

Hyogo

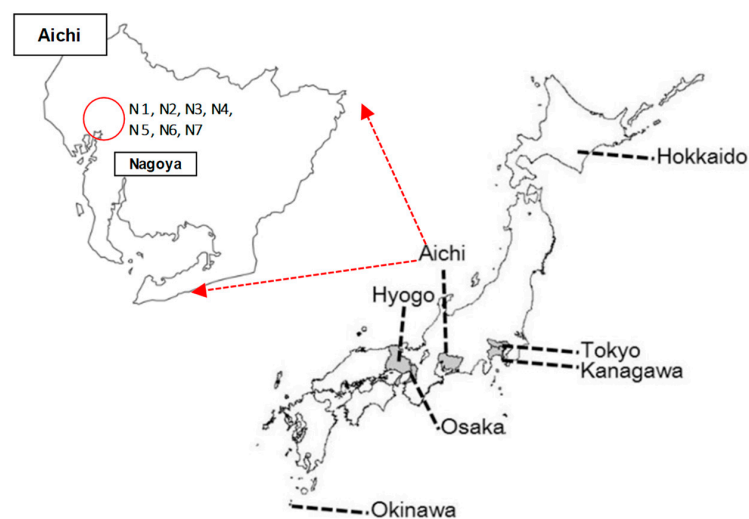Tokyo
Kanagawa

Osaka

Okinawa

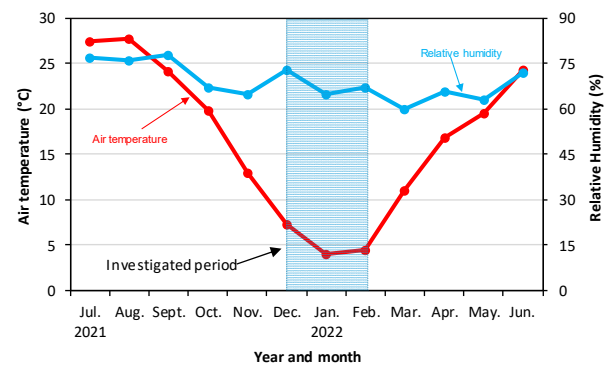**Figure 2.** Location of the investigated office buildings [27].

Figure 3. Monthly mean outdoor air temperature and relative humidity in Nagoya (Japan Meteorological Agency [28]).

The field survey was conducted in seven office buildings which were further classified as five MM and two HVAC office buildings located in the Aichi prefecture from December 2021 to February 2022. The MM buildings were selected if they had operable windows for thermal adjustment. The HVAC buildings with fixed windows were also selected to compare with MM buildings. The five investigated office buildings were of change-over mixed-mode type defined as having operable door/windows and HVAC systems depending on the seasons or time of the day [29]. Two HVAC office buildings used heating or cooling throughout the year. Figure 4 shows the general overview of the seven investigated office buildings.
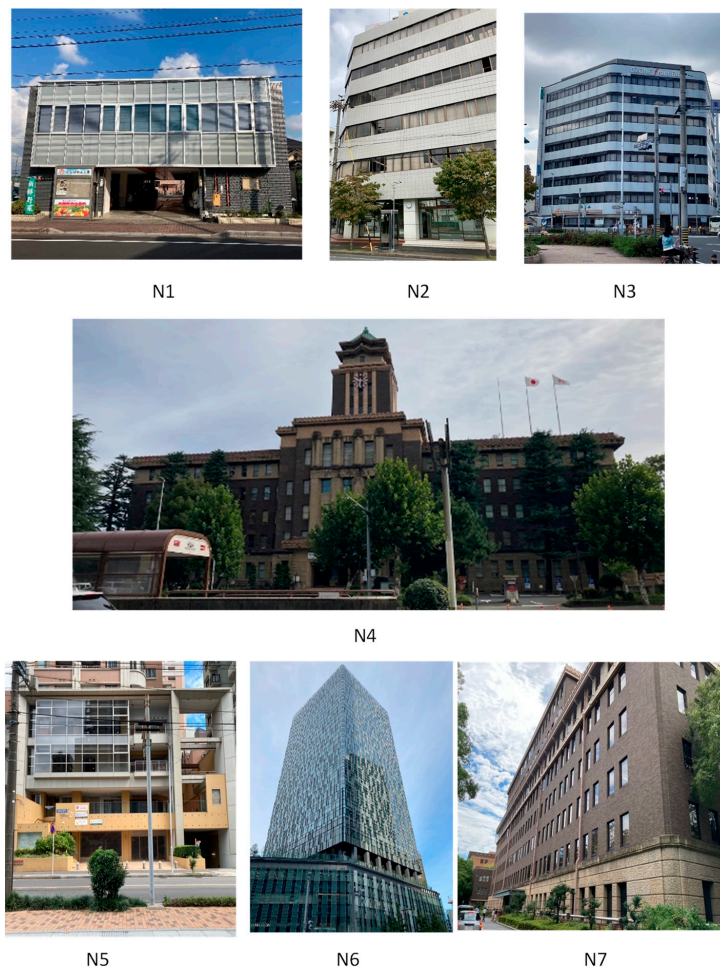

Figure 4. Overview of the investigated office buildings (N1~N7).

2.2. Thermal Measurements

The indoor environmental variables were measured by using instruments as shown in Table 2. The environmental variables were air temperature and relative humidity, measured by a digital instrument sensor, which was placed 1.1 m above the floor level, away from direct sunlight at ten-minute interval. In seven office buildings, 12 instruments were installed (Table 3). The survey method was the same as the survey conducted in the Kanto region of Japan [15].

Table 2. Description of the instrument used.

Parameter Measured	Name of the Instruments	Range	Accuracy
Air temperature Relative humidity	TR-76Ui and TR-74Ui	0 to 55 °C, 10–95% RH	±0.5 °C ±5% RH, at 25 °C, 50% RH

Table 3. Description of buildings, instruments and occupants.

Building Code	Investigated Floor	Mode	Number of Measurement Points	Number of Occupants	Number of Females	Number of Males	Number of Votes
N1	2F	MM	2	4	2	2	522
N2	1F, 2F	MM	2	8	5	3	939
N3	4F	HVAC	1	1	1	-	2
N4	2F	MM	1	8	3	5	839
N5	4F	MM	2	10	1	9	764
N6	27F	HVAC	3	10	4	6	1100
N7	5F	MM	1	5	2	3	300
Total			12	46	18	28	4466

2.3. Thermal Comfort Survey

The questionnaire sheets were distributed to the office workers of each office where the purpose of the survey and how to fill out the questionnaire were explained briefly. Moreover, the N6 and N7 office buildings carried out the survey through an excel sheet on a PC. The longitudinal survey was conducted each day by the occupants while digital instruments were installed at the office buildings for that period of time. The thermal comfort survey was conducted with 46 occupants: 28 males and 18 females (Table 3). Generally, the occupants voted 4 times a day: 2 times in the morning and 2 times in the afternoon. The survey was conducted in Japanese.

Table 4 shows the scale used for the thermal sensation vote. The full questionnaire sheet is shown in Appendix A. Each state of heating use, cooling use and window opening was recorded in binary form during the survey (0 = heating/cooling off or window closed, 1 = heating/cooling on or window open). We collected 4466 votes from seven office buildings (MM = 3364 votes and HVAC= 1102 votes).

Table 4. Scale of thermal sensation vote.

No.	Scale
1	Very cold
2	Cold
3	Slightly cold
4	Neutral
5	Slightly hot
6	Hot
7	Very hot

2.4. Calculation of Comfort Temperature

2.4.1. Regression Method

Regression analysis is the most common method used to examine the trend of the mean response over the range of temperatures encountered [3,30]. The relationship that links thermal sensation and the indoor air temperature can be expressed as a linear equation that predicts thermal sensation from the indoor air temperature.

$$TSV = a\,T_i + b \tag{1}$$

where *TSV* is the thermal sensation vote, a is the gradient of the line (regression coefficient), T_i is the independent variable (indoor air temperature in this case) and b is the intercept on the vertical axis.

2.4.2. Griffiths' Method

Based on the occupants' votes of thermal sensation and the corresponding values of measured indoor air temperature, we estimated the comfort temperature by using the following Griffiths' equation [31,32]:

$$T_c = T_i + (4 - TSV)/a \tag{2}$$

where T_c is the comfort temperature (°C) and a is Griffiths' constant (=0.50).

The previous studies [21] show that when using each Griffiths' constant (0.25, 0.33 and 0.50), there was hardly any differences in the results obtained for the mean comfort temperature. Therefore, we used a Griffiths' constant of 0.50 to estimate the comfort temperature, similar to other studies [15,32]. The comfort temperature calculated using a coefficient 0.50 is a representation of a 2 °C rise for a unit change in thermal sensation vote.

3. Results and Discussion

The data were divided into MM and HVAC for the analysis. The data of MM buildings were further categorized as free-running mode (FR), and heating mode (HT). During FR, the office buildings do not make any use of mechanical heating or cooling, and in HT, the office buildings use heating systems such as air-conditioning and heater to keep a warm indoor environment. All the data were analyzed by SPSS version 19.

3.1. Distribution of the Outdoor and Indoor Air Temperatures during the Voting

To know the investigated conditions during the voting, indoor and outdoor air temperature were analyzed. The thermal condition of MM and HVAC buildings might be different, and thus we analyzed them separately. We also needed to clarify how these buildings behaved for a given outdoor air temperature.

The mean outdoor air temperature was 7.3 °C and 7.8 °C for MM and HVAC office buildings, respectively. Figure 5 shows the distribution of the indoor air temperature. The mean indoor air temperature during the voting was 24.5 °C and 24.3 °C for MM and HVAC office buildings, respectively. The standard deviation of indoor air temperatures in MM buildings was higher than that of HVAC buildings. The result also showed that the occupants were mostly maintaining the indoor air temperature at a range of 23–27 °C in MM condition whereas it was 24–26 °C in the HVAC condition in response to the low outdoor air temperature, which was similar to that of Shahzad and Rijal [24]. The results suggest that the mean indoor air temperature of the office buildings was significantly higher than that of the value recommended by Japanese government: 20 °C.
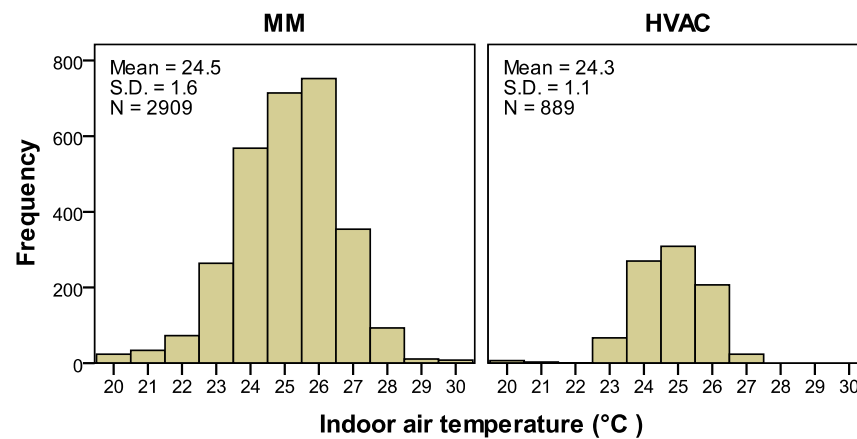
Figure 5. Distribution of indoor air temperature in MM and HVAC.

Figure 6 shows the relation between indoor and outdoor air temperatures with a 95% band of data points. With the increase in outdoor air temperature, indoor air temperature is also increasing. The reason might be that the occupants opened the windows and introduced fresh air directly through them in MM buildings, and outdoor fresh air was introduced by the air conditioning system in HVAC buildings. The heating temperature setting may also have been different in these buildings for a given outdoor air temperature. The range of indoor air temperatures was small compared to that of outdoor air temperatures in both MM and HVAC buildings. We found the following regression equations from the regression analysis.

$$\text{MM } T_i = 0.13\, T_{out} + 23.6 \quad (N = 2909,\ R^2 = 0.08,\ \text{S.E.} = 0.008,\ p < 0.001) \tag{3}$$

$$\text{HVAC } T_i = 0.16\, T_{out} + 23.0 \quad (N = 889,\ R^2 = 0.28,\ \text{S.E.} = 0.008,\ p < 0.001) \tag{4}$$

$$\text{Overall } T_i = 0.13\, T_{out} + 23.5 \quad (N = 3798,\ R^2 = 0.10,\ \text{S.E.} = 0.007,\ p < 0.001) \tag{5}$$
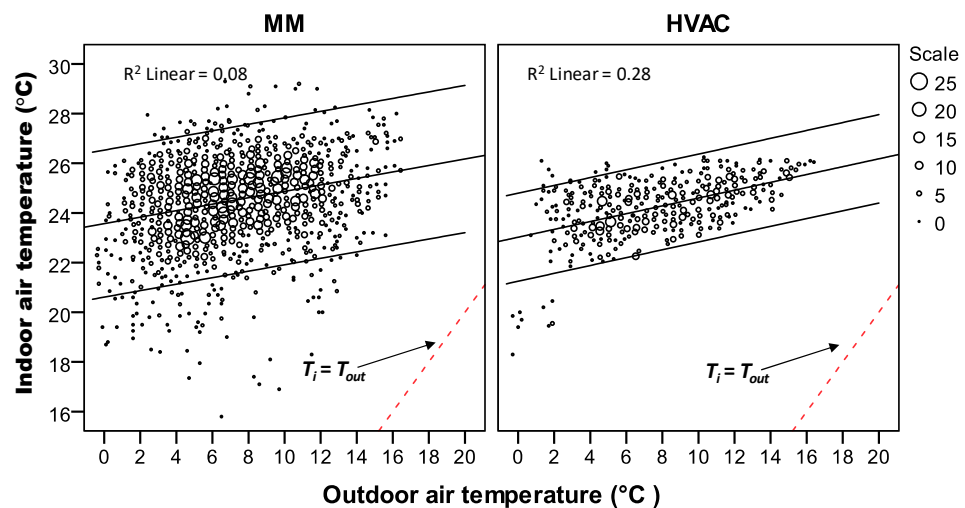
Figure 6. Relationship between the indoor and outdoor air temperatures with a 95% band of data point.

T_{out}: outdoor air temperature (°C), N: number of the sample, R^2: coefficient of determination, S.E.: standard error of the regression coefficient and *p*: significant level of regression coefficient.

The coefficient of determination in MM buildings was lower than that of HVAC buildings. The reason might be that the indoor air temperature distribution was wide in MM buildings as occupants were opening the windows during the heating cycle to

minimize the risk of COVID-19. The indoor air temperature band of MM (± 3 °C) was wider than HVAC (± 2 °C) buildings. Arens et al. [33] found that it required more energy to maintain a narrow indoor temperature range than a wider range. MM buildings had 6.2% (= $209/3364 \times 100$) of votes from the FR mode, which did not use any energy to control the indoor thermal environment. These suggest that the MM buildings might be effective for energy saving. Due to the heating use in MM and HVAC buildings, the regression coefficient or correlation coefficient was significantly low. It was weak, but the indoor air temperature was significantly correlated to the outdoor air temperature. The equations can be used to estimate the indoor air temperature of similar office buildings. For example, if the outdoor air temperature was 10 °C, the indoor air temperature would be 24.9 °C in MM buildings and 24.6 °C in HVAC buildings.

3.2. Distribution of Thermal Sensation Vote

In the previous section, we analyzed the indoor and outdoor air temperatures. In this section, we evaluate the thermal response of the office workers for a given thermal environmental condition. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) defines thermal comfort as "the condition of the mind in which satisfaction is expressed with the thermal environment" [9]. A subjective evaluation is required to understand the actual thermal comfort of occupants in office buildings.

Figure 7 shows the distribution of thermal sensation votes in MM and HVAC buildings. The mean thermal sensation vote for MM and HVAC buildings was obtained as 3.8 and 3.7, respectively. The occupants mostly voted "4. Neutral", which accounted for 72% and 70% of the votes in MM and HVAC buildings. Generally, thermal sensation votes "3. Slightly cold", "4. Neutral" and "5. Slightly hot" are considered as the thermal comfort zone and it accounted for 99% and 91% of votes for MM and HVAC buildings respectively. The results showed that the occupants were highly satisfied with the office thermal environment, but the thermal satisfaction level of MM was higher than that the HVAC buildings. However, about 4% of votes in MM and 5% of votes of HVAC buildings were "5. Slightly hot" in winter, and thus energy could be saved by reducing the temperature settings in the offices.
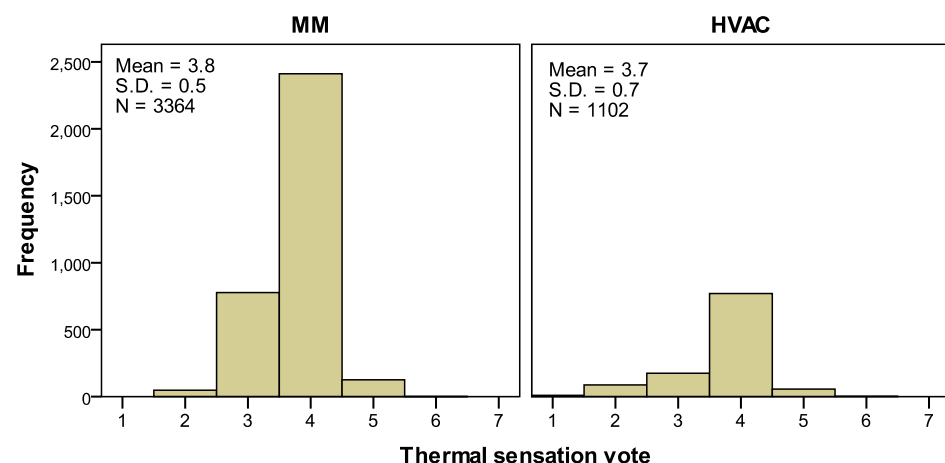
Figure 7. Distribution of thermal sensation votes.

3.3. Comfort Temperature

Comfort temperature is defined as the temperature judged by a population to be neutral on the ASHRAE scale, or comfortable on the Bedford scale: this is usually assumed to be the desired temperature [3]. It is considered as one of the key variables to understand the thermal comfort of office workers. It is used as the standard to adjust the indoor thermal environment and to give satisfactory thermal comfort to the occupants. Humphreys [34] found that the comfort temperature varied according to the region and seasons. Later, de Dear and Brager [11] also confirmed this finding from a field survey. In this

section, we want to clarify and establish the winter comfort temperature in MM and HVAC office buildings.

3.3.1. Regression Method

In this section, we analyzed the comfort temperature by a regression method similar to other studies [35–38]. The linear regression analysis of the thermal sensation votes (TSVs) and indoor air temperature for the raw and binned data was conducted as shown in Figure 8. The thermal sensation was positively correlated with the indoor air temperature. The indoor air temperature data were binned at 1 °C intervals according to the building, by applying a weighted linear regression which was similar to that of other studies [15,39]. The regression line indicated that the thermal sensation votes of HVAC buildings were more related to the indoor air temperature. We obtained the following regression equations.

$$\text{MM Raw } TSV = 0.11\, T_i + 1.2 \ (N = 2909, R^2 = 0.10, \text{S.E.} = 0.006, p < 0.001) \tag{6}$$

$$\text{Binned } TSV = 0.11\, T_i + 1.2 \ (N = 2909, R^2 = 0.57, \text{S.E.} = 0.002, p < 0.001) \tag{7}$$

$$\text{HVAC Raw } TSV = 0.29\, T_i - 3.3 \ (N = 889, R^2 = 0.17, \text{S.E.} = 0.022, p < 0.001) \tag{8}$$

$$\text{Binned } TSV = 0.26\, T_i - 2.6 \ (N = 889, R^2 = 0.88, \text{S.E.} = 0.003, p < 0.001) \tag{9}$$

$$\text{Overall Raw } TSV = 0.13\, T_i + 0.6 \ (N = 3798, R^2 = 0.11, \text{S.E.} = 0.006, p < 0.001) \tag{10}$$

$$\text{Binned } TSV = 0.13\, T_i + 0.7 \ (N = 3798, R^2 = 0.58, \text{S.E.} = 0.002, p < 0.001) \tag{11}$$
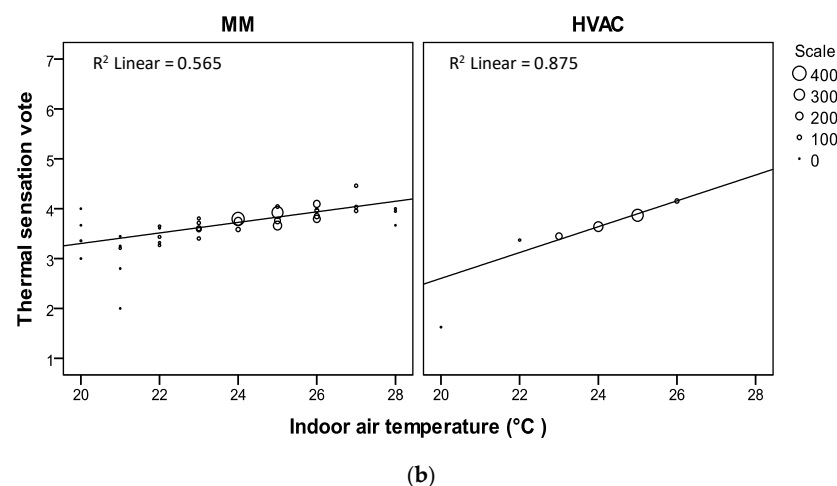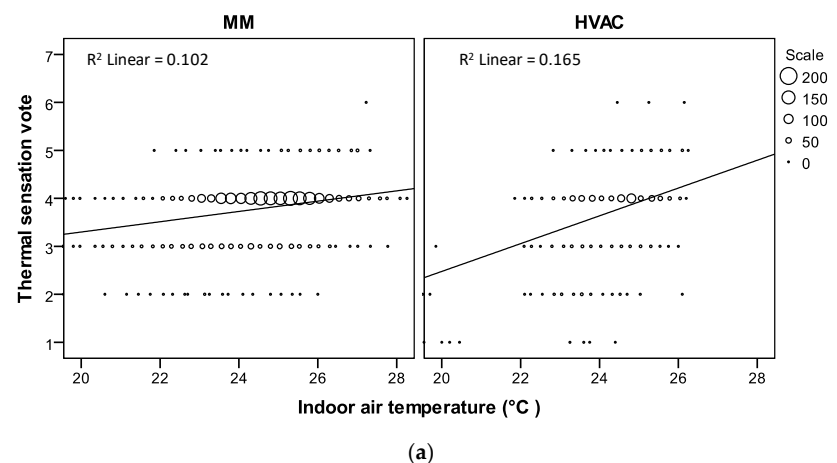

(a)

(b)

Figure 8. Relationship between thermal sensation vote and indoor air temperature: (**a**) raw data and (**b**) binned data.

The equations of raw data were almost similar to those of the binned data. However, the coefficient of determination of the binned data was much higher than that of the raw data. The slopes for the raw data of MM and HVAC buildings and overall were 0.11/°C, 0.29/°C and 0.13/°C, which indicated that for every 9.1 °C, 3.4 °C and 7.7 °C, respectively, of change in indoor air temperature, the thermal sensation vote had a unit change. The slope of MM buildings was especially unreliable. These trends were similar in previous studies conducted in different areas as shown in Table 5. In a climate chamber study, Fanger [40] found a regression coefficient of 0.33 where the temperature change required to shift a unit thermal sensation vote (T_{req}) would be 3 °C (= 1/0.33). According to Nicol et al. [41], a regression coefficient of 0.25 was often obtained in a field survey, and thus up to 4 °C of temperature required to change one thermal sensation vote might be reasonable. The field survey conducted in Japanese dwellings [42] and Nepalese dwellings [43] also obtained a low slope which was similar to this study. Kumar et al. [38] stated that the lower slope was an indication of the higher adaptation of the occupants to the indoor environment. The low slope of this study might be due to the presence of an adaptive behavior and hence it can be misleading when used to estimate the comfort temperature by a regression method as found in previous studies [42,44]. We thus estimated the comfort temperature by Griffiths' method in the next section.

Table 5. Regression equation from previous studies.

References	Country	Areas	Mode	Scale for TSV	Equations	R^2	T_{req} (°C)
This study	Japan	Aichi	MM	1–7 **	$TSV = 0.11\,T_i + 1.2$	0.10	9.1
			HVAC		$TSV = 0.29\,T_i - 3.3$	0.17	3.4
			Overall		$TSV = 0.13\,T_i + 0.6$	0.11	7.7
Karyono [35]	Indonesia	Jakarta	NV, AC and Hybrid	±3 *	$TSV = 0.32\,T_i - 8.43$	0.41	3.2
Indraganti et al. [36]	India	Chennai and Hyderabad	NV	±3 *	$TSV = 0.26\,T_g - 7.09$	0.16	3.8
Rupp et al. [37]	Brazil	Florianopo	MM	±3 *	$TSV = 0.09\,T_{op} - 2.05$	0.03	11.1
Kumar et al. [38]	India	Jaipur	NV	±3 *	$TSV = 0.15\,T_{op} - 8.43$	0.56	6.7
Rijal et al. [21]	Japan	Tokyo, Yokohama	MM	1–7 **	FR: $TSV = 0.183\,T_g - 0.6$	0.25	5.5
			HVAC		CL: $TSV = 0.228\,T_g - 1.7$	0.08	4.4
					HT: $TSV = 0.168\,T_g - 0.3$	0.08	6.0

TSV: thermal sensation vote, *: ASHRAE scale, **: modified thermal sensation scale, R^2: coefficient of determination, T_{req}: temperature change required to shift one thermal sensation vote (°C), *TSV*: thermal sensation vote, T_g: indoor globe temperature (°C), T_i: indoor air temperature (°C), T_{op}: operative temperature (°C), FR: free-running mode, CL: cooling mode, HT: heating mode.

3.3.2. Griffiths' Method

The comfort temperature was estimated by Griffiths' method [31,32,38]. This method can be used to estimate comfort temperature with any single vote in the seven-point scale of thermal sensation given the assumption of equidistance in points. It is considered as useful when a linear regression is not reliable to estimate the comfort temperature.

Figure 9 shows the distributions of the comfort temperature. The mean comfort temperature was 25.0 °C and 24.8 °C in MM and HVAC buildings. Overall, 95% of the comfort temperatures were in the range of 21.8~28.2 °C in MM and 21.8~27.8 °C in HVAC buildings. The result showed that the mean or range of comfort temperatures was comparable to that of the indoor air temperatures during the survey as shown in the Figure 5. Again, the comfort temperature of this study was significantly higher than the recommended temperature of 20 °C for the "Warm Biz" condition for both MM and HVAC buildings. Generally, a reduction of 1 °C in indoor temperature could save 10% of heating energy in winter [3]. Rijal et al. [45] also confirmed from the literature review that the heating energy could be saved by lowering the temperature setting for heating.
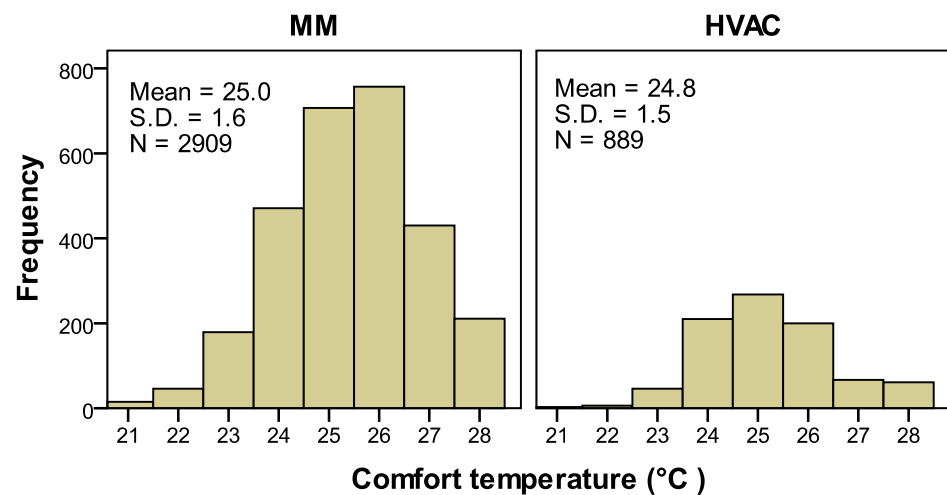
Figure 9. Distribution of comfort temperatures by Griffiths' method.

Figure 10 shows the mean comfort temperature by gender. The mean comfort temperatures in MM and HVAC buildings were quite similar but in the case of HVAC buildings, the females' comfort temperature was 1.4 °C higher than that of the males. The reason might be that the indoor air temperature in HVAC buildings was lower than that of MM buildings and females wore short skirts, and thus they may have felt colder than males. Fanger [40] concluded that there was no significant difference in comfort temperature between males and females, but our study showed opposite results. Humphreys et al. [30] found that the females were somewhat more sensitive than males to temperature. Rijal et al. [44] found that the comfort temperature for males and females was very similar (the greatest difference was in the month of November: 0.6 °C) in Japanese dwellings. The result indicated that there may be gender difference in the comfort temperature.
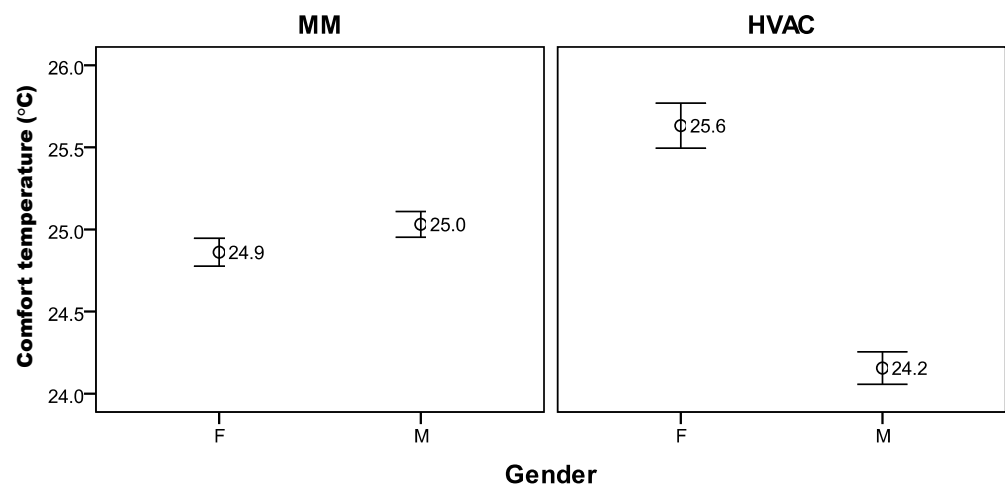
Figure 10. Comfort temperature according to gender with 95% confidence interval (mean ± 2 S.E.).

We compared the comfort temperatures in this study with that of previous studies which used the regression and Griffiths' methods as shown in Table 6. For this study, the mean comfort temperature observed was similar to that of the studies that were conducted in Kanto (Japan) and India, whereas the comfort temperature was found to be lower than that of Bangladesh, and higher than that of China, Columbia, Australia, the USA and Canada. The results indicated that the comfort temperature might be different depending on the various climatic conditions.

Table 6. Comparison of comfort temperatures with previous studies.

References	Country	Area	Building Type	Mode of Operation	Seasons	Index Temperature (°C)	Comfort Temperature (°C)	Method
This study	Japan	Aichi prefecture	Office buildings	MM HVAC	Winter	T_i	25.0 24.8	Griffiths
Rijal et al. [15]	Japan	Kanto region	Office buildings	MM	All seasons	T_g	FR = 24.9 HT = 24.3	Griffiths
Kumar et al. [46]	India	Jalandhar	Workshop	NV	Autumn + winter	T_{op}	25.9	Griffiths
Hossain et al. [47]	Bangladesh	Dhaka	Workshop	NV	Cool and dry season	T_{op}	25.9–26.1	Regression
Kumar et al. [38]	India	Jaipur	Office	NV	Winter	T_g	25.2	Griffiths
Cao et al. [48]	China	Beijing	Classroom/offices of university	Space heating	Winter	T_{op}	20.7	Regression
García et al. [49]	Columbia	Bogota	Office buildings	NV	19 February to 11 May 2018	T_{op}	23.5	Griffiths
Ballantyne et al. [50]	Australia	Highett	Office buildings	AC	4 weeks summer 5 weeks winter (1974)	ET	21.3	Probit
Schiller et al. [51]	USA	San Francisco Bay Area	Office buildings	NV	Winter	ET	22.0	Regression
Donnini et al. [52]	Canada	Montreal, Longueuil, Gramby, Cap-de-la-Medeliene, Shawinigan, Trois Rivieres, Hull and Maniwaki	Office buildings	Heated in winter cooled in summer	Winter	ET	23.1	Probit

T_i: indoor air temperature, T_g: indoor globe temperature, T_{op}: operative temperature, *ET*: effective temperature.

3.4. Relationship between the Comfort Temperature and Indoor Air Temperature

Humphreys [53] found that if the occupants had adapted to their indoor temperature, the optimum temperature for comfort should be highly correlated with the mean temperature they had experienced. HVAC buildings were highly controlled by using heating systems in winter, which resulted in a narrow range of indoor air temperature differences. In this section, we analyzed how the comfort temperature of MM and HVAC buildings related to the indoor air temperature, as in other studies [15,48,54,55].

A regression analysis was used to examine the relationship between comfort temperature and indoor air temperature for raw and binned data as shown in Figure 11. The data were binned at 1 °C intervals of indoor air temperatures according to the buildings, by applying a weighted linear regression similar to other studies [15,39]. When the indoor air temperature was low, the comfort temperature was slightly high, and when the indoor air temperature was high, the comfort temperature was slightly low in the raw and binned data. However, the MM buildings showed a higher correlation as the regression line was close to the diagonal line drawn ($T_c = T_i$) than that of HVAC buildings. We found the following regression equations.

$$\text{MM Raw } T_c = 0.79 \, T_i + 5.7 \ (\text{N} = 2909, \text{R}^2 = 0.60, \text{S.E.} = 0.012, p < 0.001) \tag{12}$$

$$\text{Binned } T_c = 0.76 \, T_i + 6.4 \ (\text{N} = 2909, \text{R}^2 = 0.94, \text{S.E.} = 0.004, p < 0.001) \tag{13}$$

$$\text{HVAC Raw } T_c = 0.42 \, T_i + 14.6 \ (\text{N} = 889, \text{R}^2 = 0.09, \text{S.E.} = 0.44, p < 0.001) \tag{14}$$

$$\text{Binned } T_c = 0.40 \, T_i + 15.2 \ (\text{N} = 889, \text{R}^2 = 0.87, \text{S.E.} = 0.005, p < 0.001) \tag{15}$$

$$\text{Overall Raw } T_c = 0.74 \, T_i + 6.9 \ (\text{N} = 3798, \text{R}^2 = 0.49, \text{S.E.} = 0.012, p < 0.001) \tag{16}$$

$$\text{Binned } T_c = 0.71 \, T_i + 7.6 \ (\text{N} = 3798, \text{R}^2 = 0.91, \text{S.E.} = 0.004, p < 0.001) \tag{17}$$

The coefficient of determination of the binned data was much higher than that of the raw data, which indicated a strong correlation between the indoor air temperature and comfort temperature. It is interesting to note that the slope of both raw and binned data was almost similar. The regression coefficient and the correlation coefficient of MM

buildings were much higher than those of HVAC buildings. People became more adapted to the indoor temperatures they experienced in MM buildings, while at the same time they adjusted the indoor temperature to make themselves comfortable, which was similar to the results of Rijal et al. [21]. As shown in Table 7, we found similar trends to the previous studies. If we know the indoor temperature, we can estimate the comfort temperature of similar office buildings. For example, if the indoor air temperature was 24 °C, the comfort temperature would be 24.7 °C in MM and HVAC buildings for the raw data.
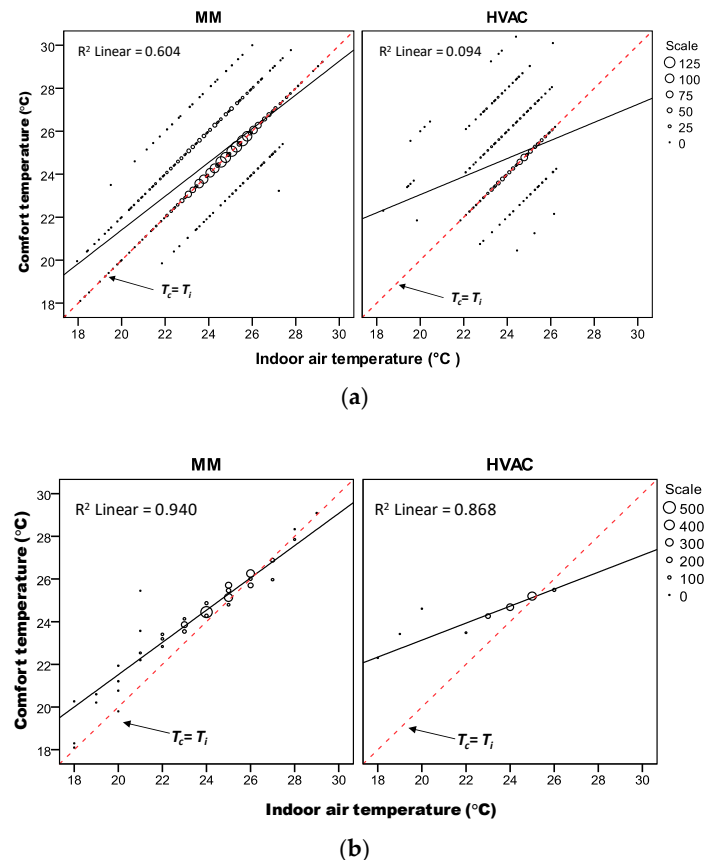

(a)

(b)

Figure 11. Relationship between comfort temperature and indoor air temperature: (**a**) raw data and (**b**) binned data.

Table 7. Comparison of comfort temperature and indoor temperature.

References	Country	Area	Mode	Season	Equation	R^2
Rijal et al. [15]	Japan	Tokyo, Kanagawa	MM and HVAC	All seasons	$T_c = 0.74\, T_g + 6.9$	0.34
García et al. [49]	Columbia	Bogota	NV	19th February to 11th May 2018	$T_c = 0.72\, T_i + 6.5$	0.45
Kuchen and Fisch [54]	Germany	Berlin, Braunschweig, Hamburg, Hannover, Gelsenkirchen, Helmstedt, Leverkusen, Magdeburg, Mannheim, Osnabruck, Wolfburg	MM, AC and NV	Winter	$T_c = 0.82\, T_{op} + 3.85$	0.79
Nicol et al. [55]	Pakistan	Karachi, Multan, Peshwar, Quetta, Saidu Sharif	MM and HVAC	Summer and winter	$T_c = 0.55\, T_g + 11.7$	0.82

T_c: comfort temperature (°C), T_g: indoor globe temperature (°C), T_i: air temperature (°C), T_{op}: operative temperature (°C), R^2: coefficient of determination.

4. Discussion

The current study of a daily field survey in winter investigated the comfort temperature in five MM and two HVAC office buildings of the Aichi prefecture. In this study, a comparison of the thermal sensation and comfort temperature was shown between MM and HVAC office buildings. The subjective evaluation of the thermal comfort of the occupants was satisfactory in both MM and HVAC offices. While considering the comfort zone of the seven-point scale, 99% of votes in MM and 91% in HVAC buildings were in that range, which showed that the MM was more resilient than HVAC in terms of thermal comfort.

The comfort temperature estimated using a regression method indicated that it was not a suitable method as the slope of the equation obtained was small. The slope of this study was similar to that of previous studies [21,35–38]. Therefore, Griffiths' method was adapted to estimate the comfort temperature. The comfort temperatures obtained by Griffiths' method for MM and HVAC buildings were 25.0 °C and 24.8 °C, respectively. However, the value obtained for the comfort temperature was found to be 4~5 °C higher than the Japanese government's recommendation. In such a case, if the indoor air temperature could be lowered gradually, then it might be possible that the occupant would be able to adapt to the lower indoor temperature, which would eventually contribute to energy savings.

A regression analysis between the indoor air temperature and the comfort temperature was conducted. The raw data were validated by binning the data and it was found that the coefficient of determination of the binned data was higher in comparison to the raw data. Thus, a strong correlation between the indoor air temperature and the comfort temperature was obtained, similar to previous studies [15,39]. However, the slope of the raw and binned data was almost similar. The regression coefficient and correlation coefficient of MM office buildings were higher than those of HVAC office buildings. This showed that the occupants became more adapted to the indoor temperature they experienced in the MM buildings.

5. Conclusions

We conducted a daily field survey on winter comfort temperature in five MM and two HVAC office buildings in the Aichi prefecture of Japan. We found the following results:

1. The proportion of neutral thermal sensation was 72% and 70% in MM and HVAC buildings. The percentage of the votes in the comfort zone was 99% and 91% in MM and HVAC buildings. Thus, the occupants were highly satisfied with their office environment, but they were more satisfied in MM buildings.
2. Overall, 95% of the comfort temperatures were in the range of 21.8~28.2 °C in MM and 21.8~27.8 °C in HVAC buildings, which were higher than the recommended value (20 °C) of the Japanese government for the winter. If we reduced the temperature setting similar to the recommended value, a significant amount of heating energy could be saved.
3. The comfort temperature and indoor air temperature were highly correlated in MM buildings. The result indicated that the occupants adapted more to the given thermal environment of MM buildings than that of HVAC buildings.

In conclusion, this research indicated that the occupants were satisfied with the indoor thermal environment of the investigated office buildings. Although the Japanese government recommends an indoor temperature of 20 °C for heating, the mean comfort temperature was found to be 5.0 °C and 4.8 °C higher in MM and HVAC buildings, respectively. If the indoor air temperature could be lowered gradually, then occupant would be able to adapt to the low indoor temperature as well, because the comfort temperature was correlated with the indoor air temperature. A low indoor temperature setting would be helpful to realize the recommended temperature of the Japanese government, which would be effective for saving energy.

In this research, only the indoor air temperature was considered to estimate the comfort temperature, whereas the results from considering globe temperatures might be slightly different. Since the analysis was for the winter season, it is necessary to clarify the results from the other seasons to know the seasonal differences in comfort temperature [15,56]. A

detailed analysis of various modes should be conducted. As the field survey was a daily survey, the individual and gender differences in comfort temperature need to be analyzed. The comfort temperature was estimated considering the indoor air temperature; it should be analyzed with the outdoor temperature to propose an adaptive model. It is necessary to analyze the behavioral adaptation of the occupants such as clothing adjustments, window opening and fan use, to understand the adaptive mechanism of the occupants.

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Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

Cfa	Humid-subtropical
ET	Effective temperature (°C)
p	Significant level of regression coefficient
R^2	Coefficient of determination
T_a	Air temperature (°C)
T_c	Comfort temperature (°C)
T_g	Globe temperature (°C)
T_i	Indoor air temperature (°C)
T_{op}	Operative temperature (°C)
T_{out}	Outdoor air temperature (°C)
T_{req}	Temperature change required to shift one thermal sensation vote (°C)
AC	Air Conditioning
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
CEN	Comité Européen de Normalisation
CL	Cooling mode
FR	Free-running mode
HT	Heating mode
HVAC	Heating, ventilation, and air conditioning
MM	Mixed-mode
NV	Naturally ventilated buildings
PC	Personal computer
S.D.	Standard deviation
S.E.	Standard error
SPSS	Statistical package for the social sciences
TSV	Thermal sensation votes

Appendix A

Instrument no: [ ]　　**Thermal comfort survey of office (Daily)**　　1st 2nd 3rd 4th

Bldg.: [ ]　　**Name:** [ ]　　**Voting time →** Hour [ ][ ][ ][ ]

Dept.: [ ]　　**Date:** 202 Y　M　D　　Min.

① **Now, how do you feel about hotness and coldness?**　[ ][ ][ ][ ]

1	2	3	4	5	6	7
Very cold	Cold	Slightly cold	Neutral	Slightly hot	Hot	Very hot
			(Neighter hot nor cold)			

② **How would you prefer now?**　[ ][ ][ ][ ]

1	2	3	4	5
Much warmer	A bit warmer	No change	A bit cooler	Much cooler

③ **Can you accept hotness and coldness now?**　[ ][ ][ ][ ]

0	1
Acceptable	Unacceptable

④ **What do you think the "indoor temperature" now? (Please answer without looking the thermometer.)**　[ ][ ][ ][ ]

⑤ **How do you feel the humidity right now?**　[ ][ ][ ][ ]

1	2	3	4	5	6	7
Very dry	Dry	Slightly dry	Neutral	Slighly humid	Humid	Very humid
			(Neighter humid nor dry)			

⑥ **How would you prefer the humidity right now?**　[ ][ ][ ][ ]

1	2	3	4	5
Much more humid	A bit more humid	No change	A bit drier	Much drier

⑦ **Considering the thermal environment (temp., humidity, air movement) right now, how would you rate your overall comfort?**　[ ][ ][ ][ ]

6	5	4	3	2	1
Very comfortable	Comfortable	Slightly comfortable	Slightly uncomfortable	Moderately uncomfortable	Very uncomfortable

⑧ **How do you find the lighting level at your work desk at this time?**　[ ][ ][ ][ ]

1	2	3	4	5	6	7
Very dim	Dim	Slightly dim	Neither bright nor dim	Slightly bright	Bright	Very bright

⑨ **How do you prefer the lighting level at your work desk at this time?**　[ ][ ][ ][ ]

1	2	3	4	5
Much brighter	A bit brighter	No change	A bit dimmer	Much dimmer

⑩ **How would you describe "easiness of work" right now?**
(Please answer considering the thermal environment, humidity, air movement, brightness and air quality.)　[ ][ ][ ][ ]

6	5	4	3	2	1
Very easy to work	Easy to work	Slightly easy to work	Slightly difficult to work	Difficult to work	Very difficult to work

⑪ **Now, how is the sweating condition?**　[ ][ ][ ][ ]

1	2	3	4
None	Slightly	Moderate	Profuse

⑫ **What have you been doing in the last 15 minutes? (Please select one main activity)**　[ ][ ][ ][ ]

1 Sitting - passive	2 Sitting - active	3 Standing - light work
4 Standing - working	5 Walking - indoor	6 Walking - outdoor

⑬ **Please choose 0 or 1 for the "environmental controls" in your office now. (If you do not have, please mark "X")**

Door	0 Close	1 Open	[ ]	[ ]	[ ]	[ ]
Window	0 Close	1 Open				
Natural vent	0 Close	1 Open				
Blind	0 Close	1 Open				
AC Cooling	0 Off	1 On				
Fan	0 Off	1 On				
AC heating	0 Off	1 On				
Heater	0 Off	1 On				
Celing light	0 Off	1 On				
Desk light	0 Off	1 On				

⑭ **If you are using air conditioning in your office now, please write the "temperature setting" (if you know).**　[ ][ ][ ][ ]

⑮ **Please select the clothing insulation right now. (You can choose between the number too)**

Male — Short-sleeved shirt + short pants; long-sleeved shirt + long pants; Thin cardigan + long pants; Jacket+ long pants

0　0.1　0.2　0.3　0.4　0.5　0.6　0.7　0.8　0.9　1.0　1.1　1.2　1.3　1.4　1.5　clo

Female — T-shirt + shorts; long-sleeved shirt + long pants; Dress (long sleeves, lined); Thick cardigan + skirt; Thick sweater + long skirt

[ ][ ][ ][ ]

Thank you very much

Figure A1. The questionnaire sheet for the thermal comfort survey.

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