Study on thermal comfort zone in MM and HVAC office buildings in Aichi prefecture based on daily survey

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Abstract

Thermal comfort has been a subject discussed since 1930. Researchers are into understanding the thermal comfort of the occupant's whether at home, offices, educational institutions because the occupants have significant effects on their indoor environment. In this study we aim to understand the comfort temperature ranges in Mixed-mode (MM) and Heating, Ventilation, and Air Conditioning (HVAC) types of office buildings in Japan. The field data is collected in six office buildings located in Aichi prefecture from July 2021 to October 2022, where 16,411 responses were collected from 46 occupants. The environmental parameters such as air temperature, relative humidity, and so on were measured along with the responses. The result suggests that the office workers are highly satisfied and they are adapted to the indoor environment, as in the MM office buildings 80 % of the occupants were comfortable at the temperature range of 19~29 °C whereas in HVAC office building this range was 22~27 °C. MM office buildings had wider range of thermal comfort zone even under HT and CL mode as compared to HVAC buildings which suggests that the MM type of buildings are better than HVAC.

Keywords - Office buildings, Field survey, Thermal sensation vote, Globe temperature, Probit analysis, Thermal comfort zone.

1. Introduction

The energy consumption of the office building plays a significant role in terms of the country's overall energy consumption. In 2019, the commercial sector's buildings accounted for 30% of Japan's final energy consumption, according to the report given by the International Energy Agency [1]. The fact that fully air-conditioned office buildings with fixed windows are becoming increasingly fascinating and trendy [2]. However, the pandemic 2019 has focused on the idea of having mixed mode (MM) operated office buildings even if the office buildings are in HVAC operation mode as stated by Hayashi et al. [3]. Concurrent MM building operations are the office building having both natural ventilation and the air-condition system strategies whenever required [4]. MM buildings have the potential to offer higher degree of thermal comfort as the occupants can prefer to choose the environment according to their desire [5] and are reported to use less energy [6]. Japanese government recommend an indoor temperature of 28 °C for cooling and 20 °C for heating [7] which requires an evidence from the field survey [8] as Takasu et al. [9] mentions that this recommendation was considered focusing on making it easier for the office occupants to be comfortable based on the outdoor thermal environment. The author also adds that just by shifting the temperature and changing occupants' clothing may not achieve the improvement towards improving comfort and reducing the energy consumption [9].

According to ASHRAE 55, thermal comfort is achieved when the indoor environmental conditions can satisfy 80 % of the occupants [10]. Understanding the range of temperature to which these occupants are mostly satisfied can be considered as the thermal comfort zone. Aghniaey et al. [11] stated that it will be possible to reduce energy consumption through correct adjustment of the temperature range. Kim et al. [12] emphasized the importance of understanding the thermal sensation and the comfort zones to maximize the energy saving. In HVAC office buildings of China [13], the thermal comfort zone was obtained as 24.6-28.6 °C from 442 occupants whereas in a study conducted in the temperate climate of Romania [14], it was 22.6-26 °C in HVAC types of office buildings. These previous studies suggest that the thermal comfort zone can be obtained differently for different climatic zones.

With the above view, this study aims to determine thermal comfort zones through comparative analysis between MM and HVAC types of Japanese offices by use of probit analysis method.

2. Methods

Thermal comfort field survey was applied in MM and HVAC types of office buildings located in Aichi prefecture which lies in the central part of Japan having the climate characterized by hot and humid summers and relatively mild winters (Köppen climate classification Cfa, i.e. humid subtropical climate).

2.1 Investigated buildings and measurement period

Field studies were conducted within five MM and one HVAC office buildings located in Ichinomiya and Nagoya city of Aichi prefecture in Japan from July 2021 until October 2022. The chosen office buildings were of changeover mixed-mode type having operable windows and the HVAC systems depending on the seasons or the time of the day [4]. Table 1 summarizes the general information about the buildings, its locations and mode of operation along with their occupants. All the office buildings were equipped with HVAC systems; however, in five MM office buildings use was according to the seasons and time of the day, and one HVAC building has AC use throughout the year. Figure 1 shows the pictures of the investigated office buildings [15].

For the outdoor environmental data, it consists of daily mean, maximum and minimum temperature and the relative humidity values for the fifteen months from July 2021 until September 2022 that was collected from the meteorological station of Aichi prefecture. Figure 2 shows the monthly mean outdoor air temperature with relative humidity for the surveyed period. In case of the indoor environmental parameters, it was recorded by using the data loggers instrument set up which is placed 1.1 m above the floor level which was placed away from direct sunlight. The measurement of the indoor and the outdoor air temperature with relative humidity were collected at continuous ten-minute intervals.

Table 1: Summary of investigated office buildings and subjects

Building mode	Building code	Area	Building structure	Air-conditioning adjustment methods	No. of occupants	
					Male	Female
MM	N1	Ichinomiya City	SRC	Distributed	2	2
	N2	Nagoya City	RC	Distributed	3	5
	N4	Nagoya City	SRC	Distributed	5	3
	N5	Nagoya City	SRC	Distributed	9	1
	N7	Nagoya City	RC	Distributed	3	2
HVAC	N6	Nagoya City	SRC	Central	6	4
Total					28	17

MM: Mixed-mode, HVAC: Heating, Ventilation and Air-conditioning, SRC: Steel reinforced concrete, RC: Reinforced concrete construction

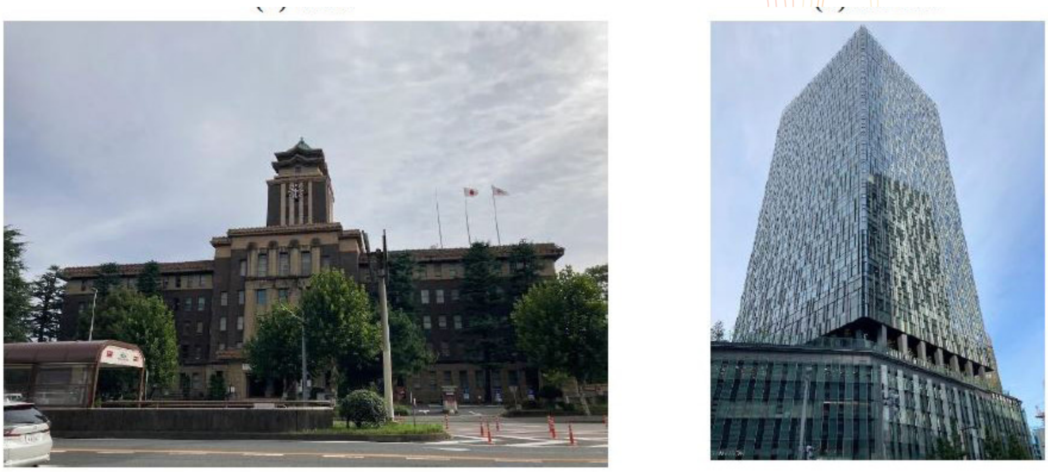


Figure 1: Overview of investigated office buildings [15]

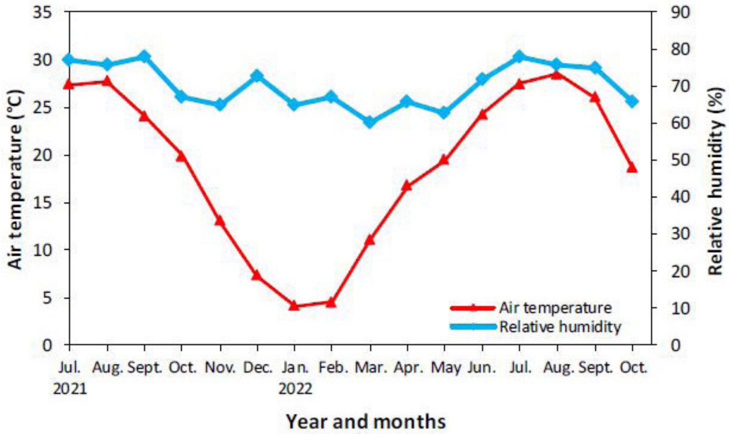


Figure 2: Monthly outdoor air temperature and relative humidity of the investigated area during survey period

2.2 Thermal comfort survey

Thermal comfort survey is a questionnaire that is used to assess the thermal comfort perceptions of the occupants' in the office buildings. The questionnaire was designed based on the work of previous researchers on the field of thermal comfort survey questionnaire which was divided into three sections. The initial section of this survey was collecting the personal information of the participants, second section was the occupants' thermal perceptions, satisfactions and the preferences. The final sections are the questions regarding the perceived level of the environmental control and its use. This survey uses the modified thermal comfort ASHRAE scale (Table 2). The questionnaire sheets were distributed to the office workers and the purpose of the survey and how to fill out the questionnaire were explained briefly in the first month of the survey started period. However, two office buildings carried out the survey using a PC. The occupants were asked to fill the questionnaire four times a day. The questionnaire was replaced every two months. The survey was conducted in the Japanese language.

Table 2: Scale of thermal sensation vote survey scale

No.	Scale
1	Very cold
2	Cold
3	Slightly cold
4	Neutral (Neither cold or hot)
5	Slightly hot
6	Hot
7	Very hot

3. Results and discussion

This research applies various analyses in the process to understand the thermal comfort of the occupants in the office buildings. The first approach is to investigate the overall environmental conditions during the survey periods following the comfort zone for the MM and HVAC office buildings with the help of probit analysis.

3.1 Thermal environment during voting

The mean outdoor air temperature and mean globe temperature for MM and HVAC office buildings are shown in Table 3 enlisting different modes (i.e. free running mode (FR), heating mode (HT), cooling mode (CL)) respectively.

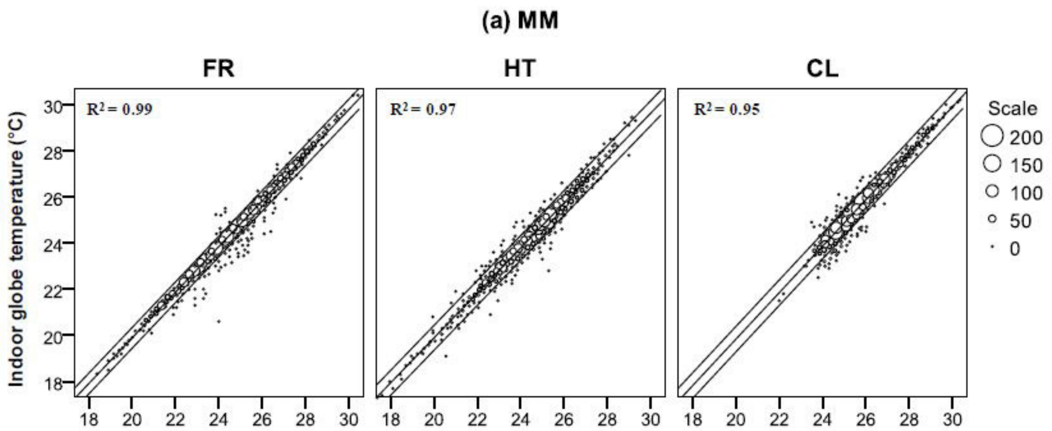
In the present study, Figure 3 indicated indoor air temperature is strongly correlated with the indoor globe temperature which is clear that these indices were similar (i.e. difference <0.5 °C) [8, 16, 17]. This result showed that any one of these temperature indexes was suitable for the later analysis process. In this study globe temperature is considered as it measures the combined effects of radiant heat, air temperature, and wind speed.

Distribution of the globe temperature is shown in Figure 4 for MM and HVAC office buildings. Most of the indoor globe temperature is obtained between 22~28 °C in MM and 22~26 °C in HVAC. The mean globe temperature of MM office buildings for HT and CL were 24.4 °C, 25.5 °C whereas in terms of HVAC buildings, they were 24.6 °C and 24.5 °C respectively. However, in consideration, with the Japanese government recommended indoor temperature of 20 °C in winter and 28 °C in summer in terms of energy savings. In this case, mean indoor temperatures during HT and CL modes were 3~4 °C different from the recommended values for both MM and HVAC office buildings. These results are similar to the previous study in Japanese office buildings [8, 16].

Table 3: Environmental parameters during voting period

Building type	Mode	N	T_{out} (°C)	T_g (°C)
MM	FR	3,943	19.4	24.6
	HT	4,592	9.8	24.4
	CL	3,984	29.0	25.5
HVAC	HT	2,685	15.1	24.6
	CL	992	25.9	24.5

MM: Mixed-mode, HVAC: Heating, Ventilation and Air-conditioning, FR: Free running mode, CL: Cooling mode, HT: Heating mode, N: Number of sample, T_{out}: Outdoor air temperature, T_g: Indoor globe temperature



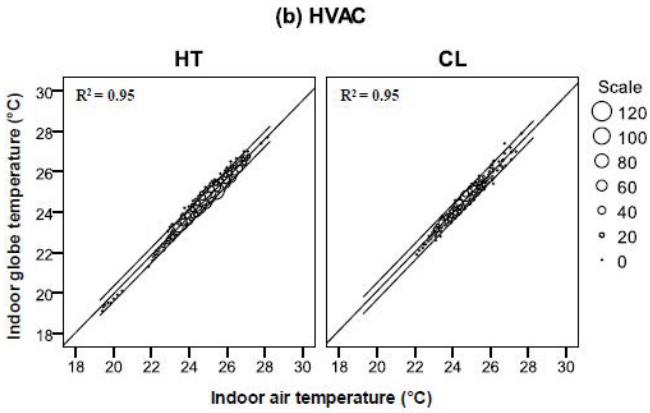


Figure 3: Relationship between indoor globe and air temperature

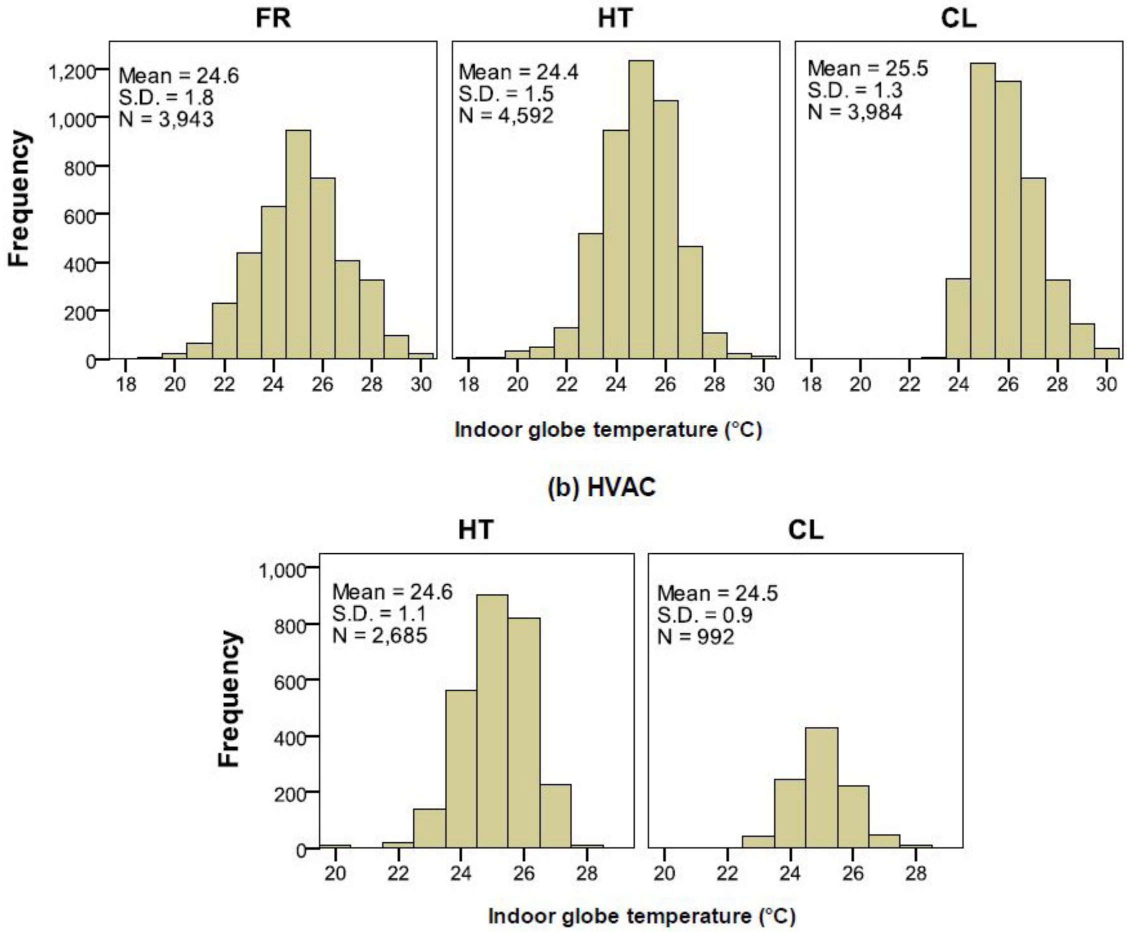


Figure 4: Distribution of globe temperature of MM and HVAC office buildings

3.2 Distribution of thermal sensation vote

Figure 5 shows the distribution of thermal sensation votes of the occupants in MM and HVAC office buildings. The highest number of votes were "4. Neutral". The mean thermal sensation vote in Figure 5 suggests that the occupants of both MM and HVAC office buildings were highly satisfied with the thermal environment of the offices as most of the votes are in comfort zones (i.e. "3. Slightly cold" "4. Neutral" and "5. Slightly hot").

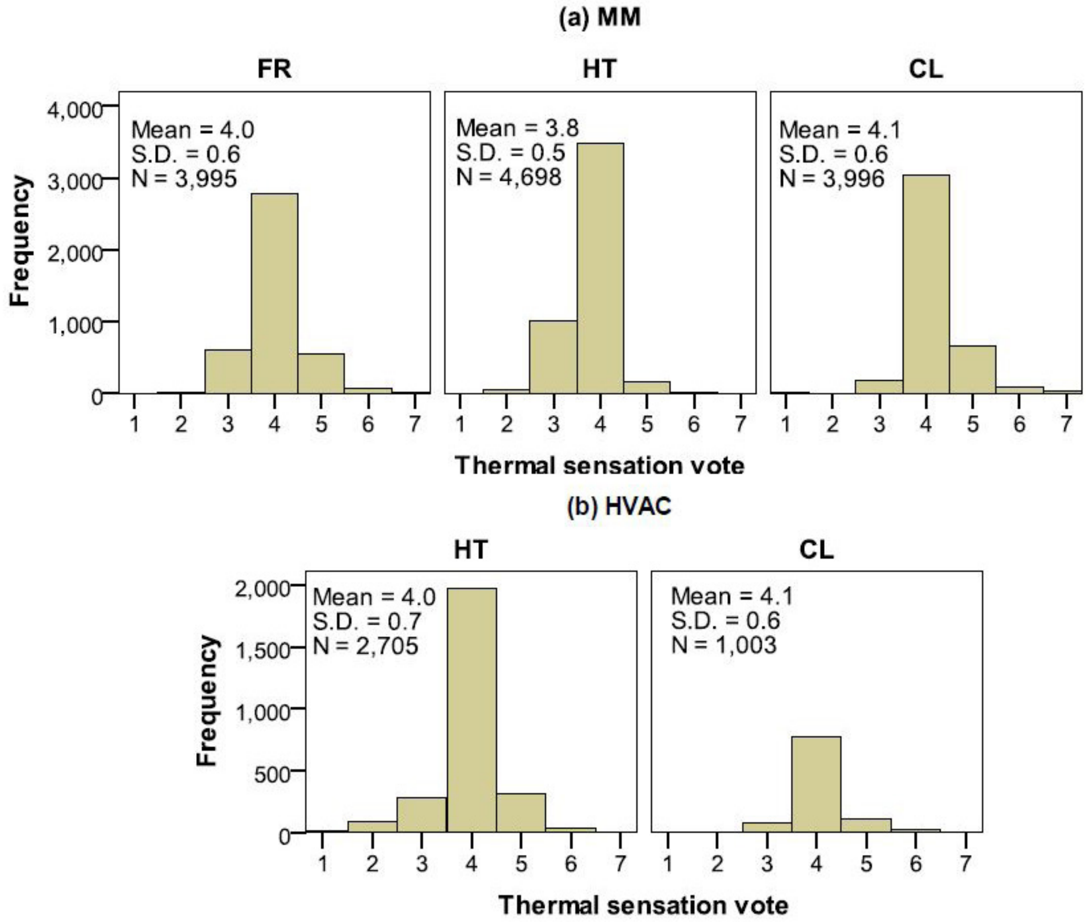


Figure 5: Distribution of thermal sensation votes

3.3 Thermal comfort zone

According to ASHRAE, thermal comfort is achieved when the indoor environmental conditions can satisfy 80 % of the occupants. Understanding the range of temperature to which these occupants are mostly satisfied can be considered as the thermal comfort zone. In this section, the thermal comfort zone is considered to be 3-5 on the subjective thermal sensation scale.

To locate the thermal comfort zone, probit regression analysis was conducted for the thermal sensation votes categories and temperature for MM and HVAC buildings. The analysis method is ordinal regression method using probit as the link function and the temperature as the covariate as done by Rijal et al. [18]. Probit analysis results are shown in Table 4. The temperature corresponding to the mean response (probit = 0) is calculated by the regression coefficient (for e.g. the mean temperature for the first equation will be 5.564/0. 0.354 = 15.7 °C). The inverse of the probit regression coefficient is considered as the standard deviation of the cumulative normal distribution (i.e. 1/0.354 = 2.8 under FR mode in MM buildings). All these calculations are calculated and shown in Table 4. After getting the equations and all the required variables, we transformed the probits using the following function into proportions which gave the curves for all the values as shown in Figure 6. The vertical axis is the proportion of the votes and comfortable.

$$Probability = CDF.NORMAL\,(quant, mean, S.D.) \qquad (1)$$

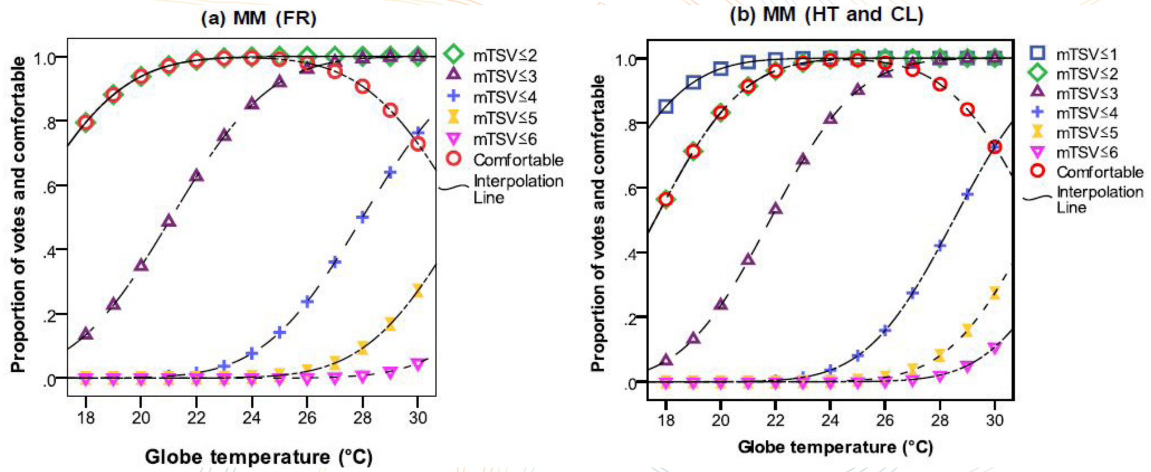
Where, CDF.NORMAL is the cumulative distribution function for the normal distribution; quant is the indoor globe temperature (°C); mean and S.D. are given in Table 4. Considering to take an example, the highest line with square markers in Figure 6 (a) defines the proportional area for TSV 1 (Very cold) and TSV 2 (Cold) and so on until the lowest line of inverted triangle 6 (Hot) and TSV 7 (Very hot) below it. As the globe temperature increased, the proportion of people who voted for TSV 2 increased, and the proportion of the occupant who voted for hot sensation increased.

Using TSV 3, 4, and 5 as the comfortable range, the probits were transformed into proportions which resulted in a bell-curve as illustrated by Rijal et al. [18]. In all meaning whether that be MM, FR mode and HT or CL mode of MM and HVAC office buildings proportion of comfort was obtained at higher level. In the MM office buildings 80 % of the occupants were comfortable at the temperature range of 19~29 °C whereas in HVAC office buildings this range was 22~27 °C. MM is further analyzed by FR category as well as HT or CL combined. The FR mode in MM office buildings showed that the range for comfort zone is 18~29 °C. HT and CL mode for MM office buildings had the comfort zone of 20~29 °C. The results suggest that MM office buildings have a wider range of comfort zones as compared to HVAC buildings. Even if we analyzed the HT and CL mode, the range of comfort zone is wider than the HVAC which means that the occupant had adaptive opportunities in the HT and CL mode in the MM office buildings. This proves that MM is better than HVAC as HVAC occupants are compelled to be comfortable in a narrow range of comfort zones.

Table 4: Probit analysis

Bldg.	Mode	Equations*	Mean	S.D.	N	R^2	S.E.
MM	FR	$TSV\ (\leq 2)$=0.354 T_g-5.564	15.7	2.8	3,941	0.23	0.012
		$TSV\ (\leq 3)$=0.354 T_g-7.481	21.1				
		$TSV\ (\leq 4)$=0.354 T_g-9.917	28.0				
		$TSV\ (\leq 5)$=0.354 T_g-11.222	31.7				
		$TSV\ (\leq 6)$=0.354 T_g-12.290	34.7				
	HT and CL	$TSV\ (\leq 1)$=0.397 T_g-6.117	15.4	2.5	8,575	0.19	0.010
		$TSV\ (\leq 2)$=0.397 T_g-7.004	17.6				
		$TSV\ (\leq 3)$=0.397 T_g-8.638	21.8				
		$TSV\ (\leq 4)$=0.397 T_g-11.319	28.5				
		$TSV\ (\leq 5)$=0.397 T_g-12.491	31.5				
		$TSV\ (\leq 6)$=0.397 T_g-13.147	33.1				
	All	$TSV\ (\leq 1)$=0.373 T_g-5.360	14.4	2.7	12,516	0.20	0.007
		$TSV\ (\leq 2)$=0.373 T_g-6.314	16.9				
		$TSV\ (\leq 3)$=0.373 T_g-8.030	21.5				
		$TSV\ (\leq 4)$=0.373 T_g-10.617	28.5				
		$TSV\ (\leq 5)$=0.373 T_g-11.828	31.7				
		$TSV\ (\leq 6)$=0.373 T_g-12.586	33.7				
HVAC	HT and CL	$TSV\ (\leq 1)$=0.534 T_g-9.928	18.6	1.9	3,687	0.17	0.021
		$TSV\ (\leq 2)$=0.534 T_g-10.946	20.5				
		$TSV\ (\leq 3)$=0.534 T_g-11.821	22.1				
		$TSV\ (\leq 4)$=0.534 T_g-14.361	26.9				
		$TSV\ (\leq 5)$=0.534 T_g-15.517	29.1				
		$TSV\ (\leq 6)$=0.534 T_g-16.569	31.0				

Notes: *All regression coefficient are significant ($p<0.001$).
TSV(≤1): Probit of the proportion of vote that is for 1, *TSV(≤1)*: Probit of the proportion of vote 2 and so on, S.D.: Standard deviation, N: Number of sample, R^2: Coefficient of determination and S.E.: Standard error of the regression coefficient



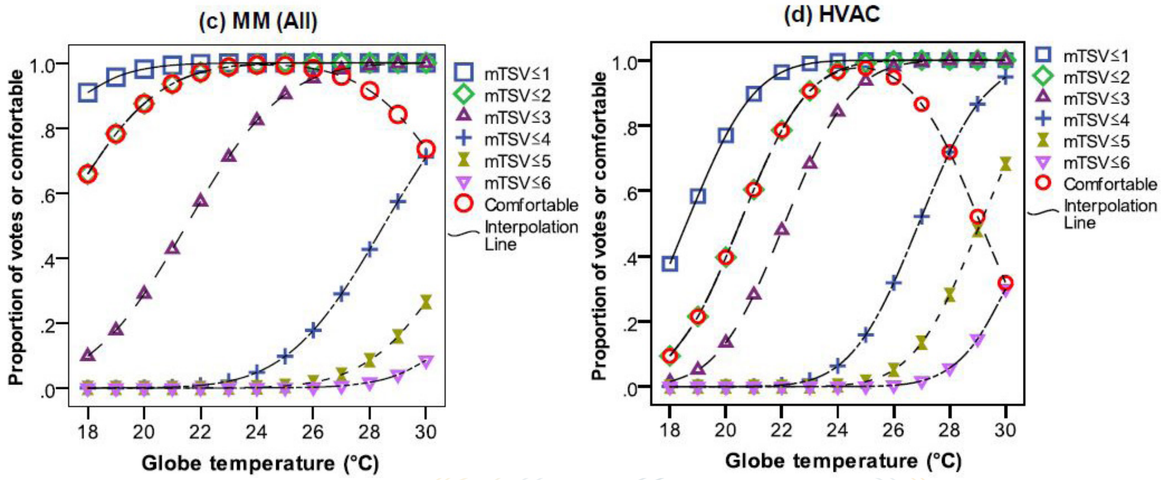


Figure 6: Proportion of votes or comfortable

4. Conclusions

By analysing the data from the field survey at Aichi prefecture, Japan in five MM and one HVAC office building the following conclusions are obtained.

1. The mean globe temperature of MM office buildings for HT and CL were 24.4 °C and 25.5 °C whereas in terms of HVAC buildings, they were 24.6 °C and 24.5 °C respectively. These mean indoor temperatures for HT and CL modes were 3~4 °C different from the recommended values by the Japanese government.

2. The occupants are satisfied with the thermal environment of both MM and HVAC office buildings as most of the thermal sensation votes were in the comfort zone (i.e. "3. Slightly cold" "4. Neutral" and "5. Slightly hot"). From all the data 98% of the occupants in MM and 95% in HVAC were in the comfort zone.

3. MM office buildings had a wider range of thermal comfort zones even under HT and CL mode (20~29 °C) as compared to HVAC buildings (22~28 °C) which suggests that the MM type of buildings are better than HVAC.

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