Development of the adaptive model for thermal comfort in office buildings of Aichi prefecture, Japan

Hom B. Rijal[1] , *Shotaku* Okamoto[1], *Supriya* Khadka[1], *Katsunori* Amano[2], *Teruyuki* Saito[2], *Hikaru* Imagawa[3], *Tomoko* Uno[4], *Kahori* Genjo[5], *Hiroshi* Takata[6], *Kazuyo* Tsuzuki[7], *Takashi* Nakaya[8], *Daisaku* Nishina[9], *Kenichi* Hasegawa[10], *Taro* Mori[11]

[1] Tokyo City University, 3-3-1 Ushikubo-nishi, Tsuzuki-ku, Yokohama 224-8551
[2] Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603
[3] Osaka Institute of Technology, 5-16-1 Omiya, Asahi-ku, Osaka 535-8585
[4] Mukogawa Women's University, 1-13 Tozaki-cho, Nishinomiya 663-8121
[5] Nagasaki University, 1-14 Bunkyo-machi, Nagasaki 852-8521
[6] Hiroshima Institute of Technology, Hiroshima 731-5193
[7] Kansai University, 3-3-35 Yamate-cho, Osaka 564-8680
[8] Shinshu University, 4-17-1 Wakasato, Nagano 380-8553
[9] Hiroshima University, Hiroshima 739-8527
[10] Akita Prefectural University, 84-4 Tsuchiya, Akita 015-0055
[11] Hokkaido University, Kita 13 Nishi 8, Kita-ku, Sapporo 060-8628

Abstract. This study was undertaken to investigate seasonal adaptation to temperature in Japanese offices, with a view to suggesting an adaptive model for them. We measured temperatures in seven office buildings and conducted thermal comfort transverse surveys of occupants for over a year in the Aichi prefecture of Japan. We collected 1,228 samples. The occupants were found to be highly satisfied with the thermal environment in their offices. Even though the Japanese government recommends the indoor temperature of 28 °C for cooling and 20 °C for heating, we found that the comfort temperature was 2.8 °C lower in cooling mode and 4.3 °C higher in heating mode, in line with the actual indoor temperatures. The monthly variation in the temperature in the investigated offices was significantly lower than had been found in dwellings. An adaptive relationship can be derived to estimate the indoor comfort temperature from the prevailing outdoor temperature for similar office buildings.

1 Introduction

Thermal adaptation is one of the most important factors in creating a comfortable office environment. Investigating and establishing the comfort temperature of the occupants can suggest customary temperatures for office buildings, which may reduce energy use and save overall energy costs.

Comfort temperatures in Japanese offices based on field surveys have been investigated in previous studies [1-11]. However there are limitations in the research to date because of short time-periods or small samples. Comfort temperatures are likely to vary according to month, requiring long-term data to fully describe the occupants' perceptions and behavioural responses to the thermal environment in their offices.

In 2004 ASHRAE [12] introduced an adaptive standard for naturally ventilated buildings and CEN [13] proposed an adaptive standard for free-running mode. However, Japanese data were not included in the data upon which they rest. The Japanese government recommends an indoor temperature of 28 °C for cooling and 20 °C for heating, and, while not unreasonable, the recommendation lacks supporting evidence from any field survey.

In order to explore seasonal differences in the comfort temperature and perhaps develop an adaptive model for Japanese offices, thermal measurements and a thermal comfort surveys were conducted for more than 1 year in seven office buildings in Aichi prefecture of Japan.

2 Field investigation

Thermal comfort surveys were conducted and corresponding thermal measurements made in seven office buildings in the Aichi prefecture of Japan from July 2021 to October 2022 (see Table 1). The indoor air temperature, globe temperature, relative humidity and air movement were measured 1.1 m above floor level, away from direct sunlight, using a data logger [8]. Outdoor air temperature and relative humidity were obtained from the nearest meteorological station.

The thermal sensation scale is shown in Table 2. We conducted both transverse and longitudinal surveys [11] in open-plan offices. This paper analyses only the data from the transverse surveys. Respondents completed the questionnaire once a month for the transverse survey.

Table 1. Description of the investigated buildings

Building code	Location	Structure	Mode	HVAC control	Window	Number of floor	Investigated floor*
N1	Ichinomiya	SRC	MM	Local	Openable	3F	2F
N2	Nagoya	RC	MM	Local	Openable	6F	1F~3F
N3	Nagoya	SRC	HVAC	Central (Local control)	Openable (For disaster prevention)	1B, 8F	4F
N4	Nagoya	SRC	MM	Local	Openable	1B, 5F	2F
N5	Nagoya	SRC	MM	Local	Openable	1B, 17F	4F
N6	Nagoya	S, Some parts SRC	HVAC	Central (local control)	Fixed	4B, 34F	27F
N7	Nagoya	RC	MM	Local	Openable	1B, 8F	5F

HVAC: Heating, ventilation and air conditioning, MM: Mixed mode (heating in winter and cooling in summer), *: The floor is counted by American system, SRC: Steel Reinforced Concrete, RC: Reinforced concrete, S: Steel, F: Floor, B: Basement

Table 2. Scale for the thermal sensation vote

No.	Scale
1	Very cold
2	Cold
3	Slightly cold
4	Neutral (neither cold nor hot)
5	Slightly hot
6	Hot
7	Very hot

As for the method of collecting the data, the instruments were set up on the office table, and questionnaires distributed to the people seated near to the instruments. While people were filling the questionnaire, the researcher recorded the environmental controls and the physical data. However, a few people did not provide responses due to their busy schedule, and others were not in the office at the time of the monthly visit. We collected 1,228 thermal comfort votes.

3 Results and discussion

The data were divided into three groups. If heating was in use at the time of the survey visit, the data were classified as being in the heating mode (HT). If cooling was in use at the time of the visit, the data were classified as being in the cooling mode (CL). If neither heating nor cooling were in use, the data were classified as being in the free-running mode (FR).

3.1 Distribution of outdoor and indoor temperature

As shown in the Figure 1, the seasonal range of the indoor temperature was quite small, while there was a wide seasonal range of outdoor temperature. The indoor globe temperature is highly related to the indoor air temperature (Fig. 2), and so the results can be presented using the globe temperature alone.

The mean globe temperatures during the voting were 25.0 °C, 24.2 °C and 25.5 °C for FR, HT and CL modes respectively (Fig. 3). The Japanese government recommends indoor temperature of 20 °C in winter and 28 °C in summer respectively. The results show that the mean indoor temperatures during heating and cooling were quite different from those recommended.

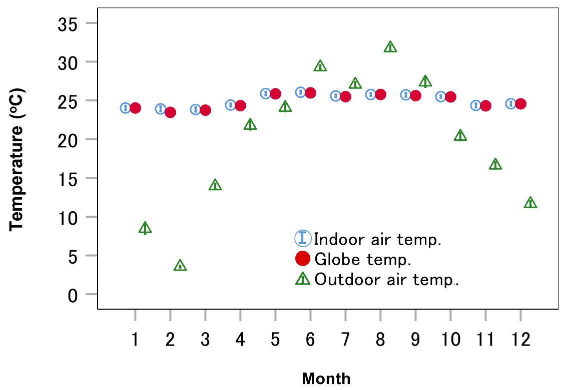

Fig. 1. Variation of outdoor and indoor temperatures (Mean±2S.E.).

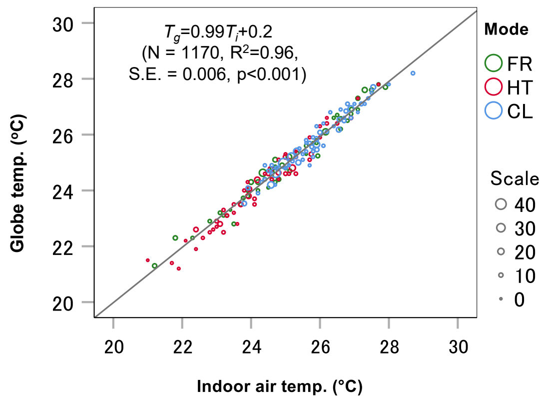

Fig. 2. Relation between the globe and indoor air temperature

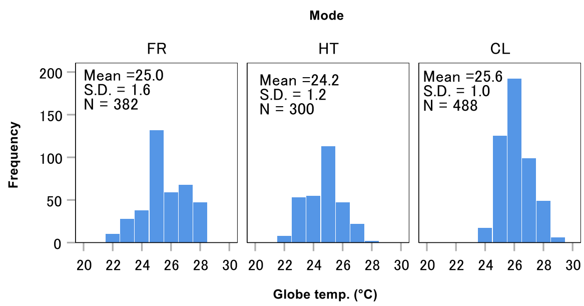

Fig. 3. Distribution of globe temperature in various modes.

3.2 Distribution of thermal sensation

Mean thermal sensation vote was 4.0, 3.9 and 4.2 in FR, HT and CL modes respectively (Fig. 4). Occupants sometimes felt hot (greater than 5) in CL mode and sometimes felt cold (less than 3) in HT mode, despite the use of heating or cooling. As there are many '4 neutral' votes in each mode, it can be said that occupants were generally satisfied in the thermal environment of the offices (Fig. 4, Table 3). It is conventional to consider as comfortable responses that fall in categories 3, 4 and 5. These percentages are very high.

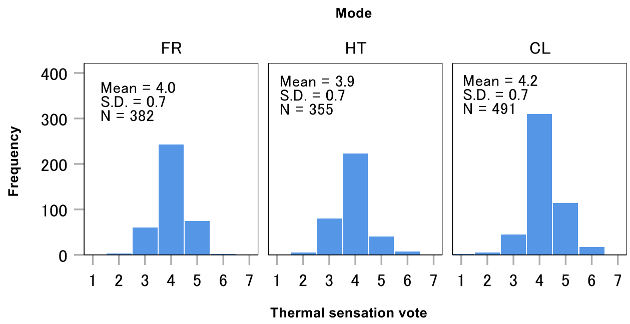

Fig. 4. Distribution of thermal sensation vote.

Table 3. Percentage of the thermal sensation vote

Scale	FR		HT		CL		All	
	N	%	N	%	N	%	N	%
1	1	0.3			2	0.4	3	0.2
2	3	0.8	5	1.4	5	1.0	13	1.1
3	60	15.7	80	22.5	44	9.0	184	15.0
4	242	63.4	223	62.8	309	62.9	774	63.0
5	74	19.4	40	11.3	114	23.2	228	18.6
6	2	0.5	7	2.0	17	3.5	26	2.1
7	-	-	-	-	-	-	-	-
Total	382	100.0	355	100.0	491	100.0	1228	100.0

N: Number of votes, %: Percentage of vote

3.3 Prediction of the comfort temperature

3.3.1 Regression method

Linear regression analysis was conducted to predict the comfort temperature. Figure 5 shows the relation between thermal sensation and globe temperature. The following regression equations are obtained for the thermal sensation vote and temperatures.

FR mode $TSV=0.14T_g+0.5$ (1)
($n=382$, $R^2=0.12$, S.E.=0.020, $p<0.001$)
HT mode $TSV=0.18T_g-0.4$ (2)
($n=300$, $R^2=0.10$, S.E.=0.031, $p<0.001$)
CL mode $TSV=0.07T_g+2.4$ (3)
($n=388$, $R^2=0.01$, S.E.=0.031, $p = 0.025$)

TSV: Thermal sensation vote; T_g: Globe temperature (°C); n: Number of sample; R^2: Coefficient of determination; S.E.: Standard error of the regression coefficient; p: Significance level of regression coefficient.

When the comfort temperature is predicted by substituting '4 neutral' in the equations (1) to (3), it would be 25.0°C, 24.4°C and 22.9°C in FR, HT, and CL modes respectively. The regression coefficients are quite low in FR and CL modes. This might be due to the problem of applying the regression method in the presence of adaptive behaviour, where it can be misleading when used to estimate the comfort temperature, as has been found in previous research [14-18]. So to avoid the problem the comfort temperature is re-estimated using the Griffiths' method.

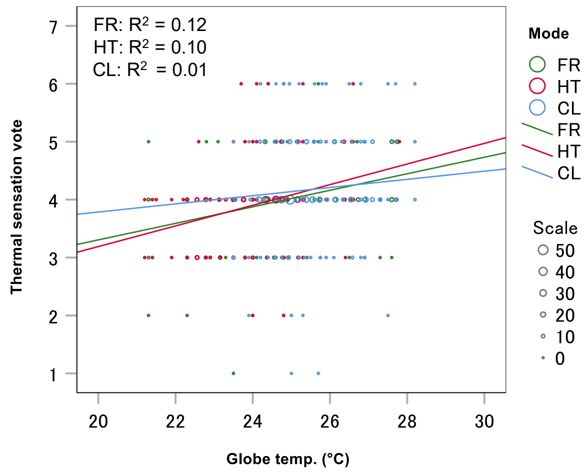

Fig. 5. Relation between the thermal sensation vote and globe temperature.

3.3.2 Griffiths' method

The comfort temperature is predicted by the Griffiths' method [19-21].

$T_c = T_g + (4 - TSV) / a$ (4)

T_c: The comfort temperature by Griffiths' method (°C); a: The rate of change of thermal sensation with room temperature.

In applying the Griffiths' method, Nicol et al. [20], Humphreys et al. [22] and Rijal et al. [8] and used values for the constant, a, of 0.50 for a 7 point thermal sensation scale. We investigated the comfort temperature using this regression coefficient.

The mean comfort temperature by the Griffiths' method is 25.0 °C, 24.3 °C, 25.2 °C in FR, HT and CL modes respectively (Fig. 6). Even though, the Japanese government recommends an indoor temperature of 28 °C for cooling and 20 °C for heating, we found that in these buildings the comfort temperature was 2.8 °C lower in CL mode and 4.3 °C higher in HT mode.

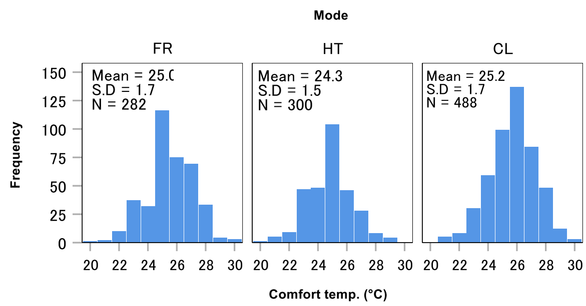

Fig. 6. Distribution of comfort temperature in each mode.

3.3.3 Monthly difference in comfort temperature

We would like to clarify the monthly difference of the comfort temperature as shown in the Figure 7. It is evident that the comfort temperature closely tracks the mean indoor globe temperature over the year. The comfort temperature and the indoor globe temperature both show rather little monthly variation. The comfort temperature is 23.9 °C in April, 26.8 °C in August in FR mode. Thus, the monthly difference of the mean comfort temperature is 2.9 K. Thus, monthly difference in comfort temperature is significantly less than was found in dwellings [14, 15, 17].

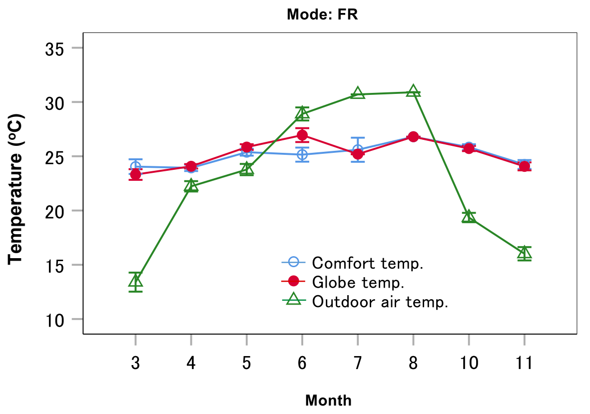

Fig. 7. Monthly mean temperature with 95% confidence intervals (Mean ± 2S.E.)

3.4 Adaptive model

An adaptive model relates the indoor comfort temperature to the outdoor air temperature [12, 13, 23-25]. Figure 8 shows the relation between the comfort temperature (calculated by the Griffiths' method) and the running mean outdoor temperature. The regression equations are given below.

FR mode $T_c=0.22T_{rm}+21.31$ (5)
($n=382$, $R^2=0.25$, S.E.=0.020, $p<0.001$)
CL&HT mode $T_c=0.05T_{rm}+23.9$ (6)
($n=788$, $R^2=0.08$, S.E.=0.006, $p<0.001$)

T_c: Comfort temperature by Griffiths' method (°C); T_{rm}: The exponentially-weighted running mean outdoor temperature for the day (°C); S.E.: The standard error of the regression coefficient. In this research, the running mean responds to the outdoor air temperature (α) is assumed to be 0.8.

The regression coefficient and the correlation coefficient in the FR mode are higher than in the CL and HT modes. The regression coefficient is lower than that in the CEN standard (FR=0.33) [13] and CIBSE [26] guide (CL&HT=0.09). It is lower than found for Japanese dwellings [14, 15]. It is probable that the low gradients which we find for the 'adaptive models' just reflect the small seasonal trends of the indoor temperatures in our sample of office buildings.

The equations can be used to predict the indoor comfort temperature for these buildings. For example, when the running mean outdoor temperature is 25 °C in equation (5), and 10 °C and 28 °C in the equation (6), the comfort temperature would be 26.6 °C, 24.4 °C and 25.3 °C for the FR, HT and CL modes respectively. The results indicate that the range of the monthly mean comfort temperature for HT & CL mode is small – less than 1K – probably because the occupants adapted only to the small seasonal variation of the temperature setting in these particular offices.

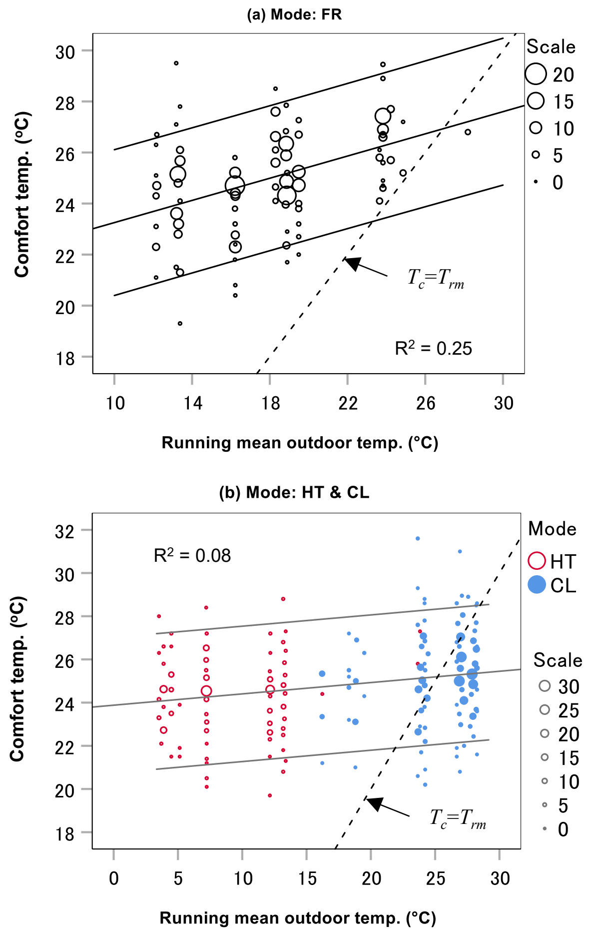

Fig. 8. Relation between the comfort temperature and running mean outdoor temperature.

4 Conclusions

A thermal comfort survey of the occupant of the Aichi prefecture of Japan was conducted more than a year in 7 office buildings. The following results were found:

1. The occupants proved to be highly satisfied with the thermal environment of their offices, as indicated by the high proportion of 'neutral' responses.
2. The average comfort temperature was found to be 25.2 °C when cooling was used, 24.3 °C when heating was used, and 25.0 °C when neither heating nor cooling were used (the FR mode). The comfort temperature for heating mode is high.
3. The monthly variation in comfort temperature in offices is significantly lower than in had been found in Japanese dwellings.
4. The seasonal variation of the comfort–temperatures tracked those of the concurrent mean indoor globe temperatures.

5. Adaptive models are proposed to estimate the indoor comfort temperature from outdoor air temperature.

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