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Investigation of comfort temperature and the adaptive model in Japanese houses

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Abstract
We have conducted the thermal measurement in the living rooms and a thermal comfort survey of residents for a year in Japan. The residents are highly satisfied with the thermal environment of their houses. Seasonal difference was found in the comfort temperature. The results showed that the comfort temperature changes with changes the indoor and outdoor climate. By using the relationship between indoors and outdoors, the adaptive model was proposed to predict and control the indoor comfort temperature.

Keywords
House; Living; Adaptive model; Thermal comfort survey; Comfort temperature

1. Introduction
Thermal comfort is one of the most important factors in creating the most comfortable homes. An understanding of the comfort temperature can be useful in the design of the residences, so as to reduce excessive use of air conditioning.
The comfort temperature of houses is well investigated in the past (Nakaya et al. 2005), Nepal (Rijal et al. 2010), Pakistan (Nicol & Roaf 1996) and UK (Rijal & Stevenson 2010). However, some researchers are conducted for a short period of time, while some collected only a few samples. The comfort temperature may also vary according to the month and season, which is not investigated in the existing research using year-round data.
Recently, ASHRAE (2004) and CEN (2007) are proposing the adaptive model for naturally ventilated and air conditioned building design. The adaptive models are based on thermal comfort survey mainly in the European and American offices, and Japanese data is not included in them. The occupants' behaviour in the office and at home is different, and thus the exiting adaptive models may not be applicable to residences.
In order to clarify the seasonal differences in the comfort temperature and to propose the adaptive model for Japanese residences, a year-round thermal measurement and a thermal comfort survey were conducted in the living rooms of residences in the Gifu region of Japan.

2. Field investigation
The thermal measurement and thermal comfort survey were conducted in 30 houses in Gifu region of Japan. The measurements period was from 13 May 2010 to 31 May 2011. The indoor air temperature and relative humidity were measured in the living

room at a ten minute interval (Fig. 1). The subjects numbered at 40 males (mean age 40.5 years old) and 38 females (mean age 41.3 years old). The thermal comfort survey was conducted several times a day using 9 point thermal sensation scale (Fig. 2). Even though the ASHRAE scale is frequently used to evaluate the thermal sensation, the words "cool" or "warm" imply comfort in Japanese, and thus the new thermal sensation scale is proposed. The number of collected samples was more than 21,000. Outdoor air temperature and relative humidity were taken from the nearest meteorological station.

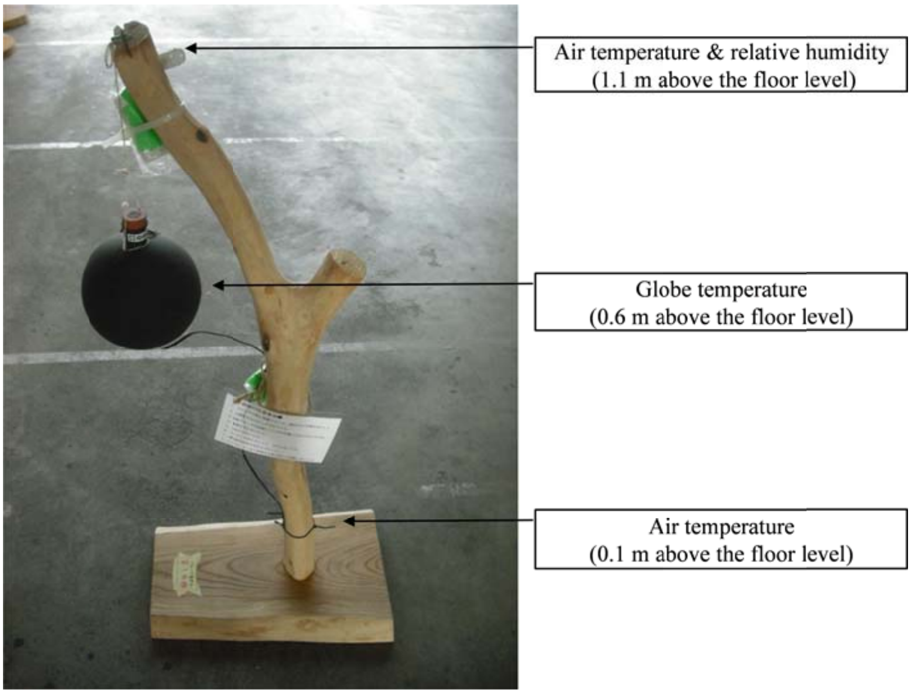

Fig. 1 Details of the thermal measurement

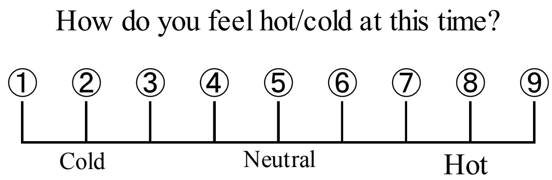

Fig. 2 Thermal sensation scale

3. Analysis methods

3.1 Prediction of the comfort temperature

In this research, the comfort temperature was predicted by regression method and Griffiths' method. In the regression method, the comfort temperature is estimated by substituting "5 neutral" in the linear regression equation of the thermal sensation and indoor air temperature. However, the prediction of the comfort temperature by the regression method may not be suitable in the field survey, and thus the comfort temperature is also investigated by the Griffiths' method (Griffiths 1990, Nicol et al. 1994, Rijal et al. 2008).

$$T_c = T_i + (5 - C) / a^* \quad (1)$$

Where T_c is the comfort temperature by Griffiths' method (°C), T_i is the indoor air temperature (°C) and a* is the regression coefficient. In applying the Griffiths' method, Nicol et al. (1994) and McCartney & Nicol (2002) used the regression coefficient of 1) 0.25, 2) 0.33 and 3) 0.50 in the 7 point thermal sensation scale. 1) 0.25 is the regression coefficient which is often obtained in the field survey. 2) 0.33 is regression coefficient from the laboratory experiment of Fanger by the Probit method. 3) 0.50 is the regression coefficient which is often used recently (Rijal et al. 2008). We have also investigated the comfort temperature using these regression coefficients. If we convert three regression coefficients into the 9 point thermal sensation scale of this research, it would be 1) 0.33 (=0.25×8/6), 2) 0.44(=0.33×8/6) and 3) 0.67(=0.50×8/6).

3.2 Running mean outdoor temperature

Running mean outdoor temperature is the exponentially weighted daily mean outdoor temperature, and it is calculated using the following equation (McCartney & Nicol 2002).

$$T_{rm} = \alpha T_{rm\text{-}1} + (1\text{-}\alpha) T_{od\text{-}1} \qquad (2)$$

Where, $T_{rm\text{-}1}$ is the running mean outdoor temperature for the previous day (°C), $T_{od\text{-}1}$ is the daily mean outdoor temperature for the previous day (°C). So, if the running mean has been calculated (or assumed) for one day, then it can be readily calculated for the next day, and so on. α is a constant between the 0 and 1 which defines the speed at which the running mean responds to the outdoor air temperature. In this research α is assumed to be 0.8.

Table 1 Mean indoor air temperature of each house

Group	House number	Number of sample	Mean (°C)	Standard deviation (°C)
A	1	1,367	23.8	4.7
	2	738	22.6	4.4
	3	688	21.1	5.8
	4	821	21.7	4.8
	5	202	25.1	3.1
	6	803	20.4	6.1
	7	799	22.1	6.4
	8	583	23.9	4.4
	9	340	24.2	4.9
	10	600	22.4	4.5
B	1	725	21.7	5.7
	2	718	20.7	6.9
	3	735	17.5	8.3
	4	540	22.9	5.2
	5	455	21.6	5.9
	6	1,533	20.7	5.6
	7	331	20.6	6.6
	8	758	23.1	4.4
	9	225	22.8	4.8
	10	192	25.4	3.9
C	1	767	20.4	6.3
	2	346	20.1	7.7
	3	807	22.6	4.8
	4	727	22.9	5.3
	5	134	25.7	4.6
	6	1,320	21.4	5.8
	7	844	20.7	7.9
	8	641	24.6	5.3
	9	1,129	22.5	4.7
	10	851	21.6	3.7
All		20,719	21.9	5.8

4. Results and discussion

4.1 Distribution of indoor temperature

In order to clarify the indoor air temperature during the voting, the distribution of indoor air temperature is shown in Fig. 3. Mean indoor air temperature of each house is shown in Table 1. The data was divided in the NV mode (Naturally ventilated), AC mode (cooling by air conditioning) and HT mode (heating).

The mean indoor air temperature during the voting is 22.7°C in NV mode, 28.0°C in AC mode and 17.6°C in HT mode. Mean outdoor air temperature is 18.8°C for NV mode, 28.9°C for AC mode and 6.7°C for HT mode (Fig. 4). The result shows that seasonal difference of the indoor or outdoor air temperature is considerably high.

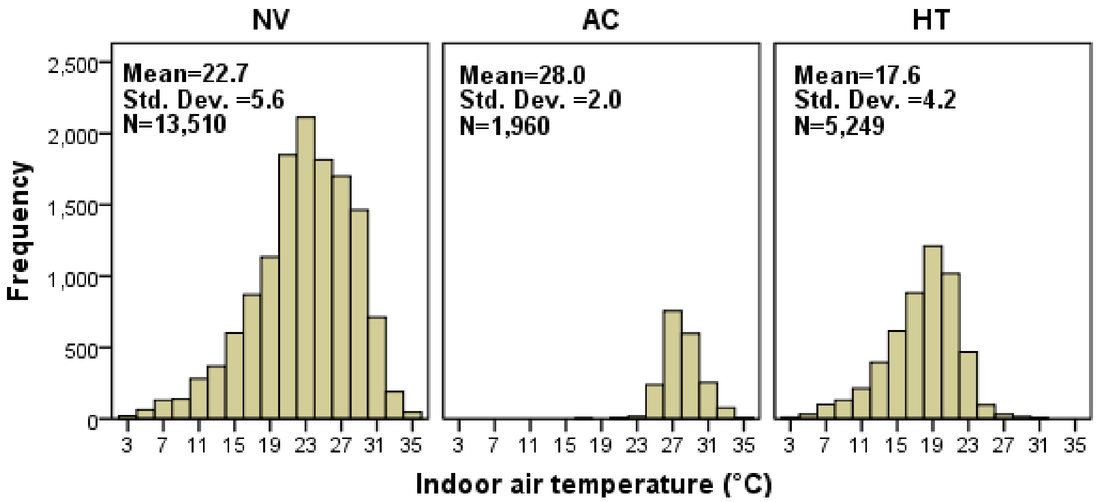

Fig. 3 Distribution of indoor air temperature during the voting

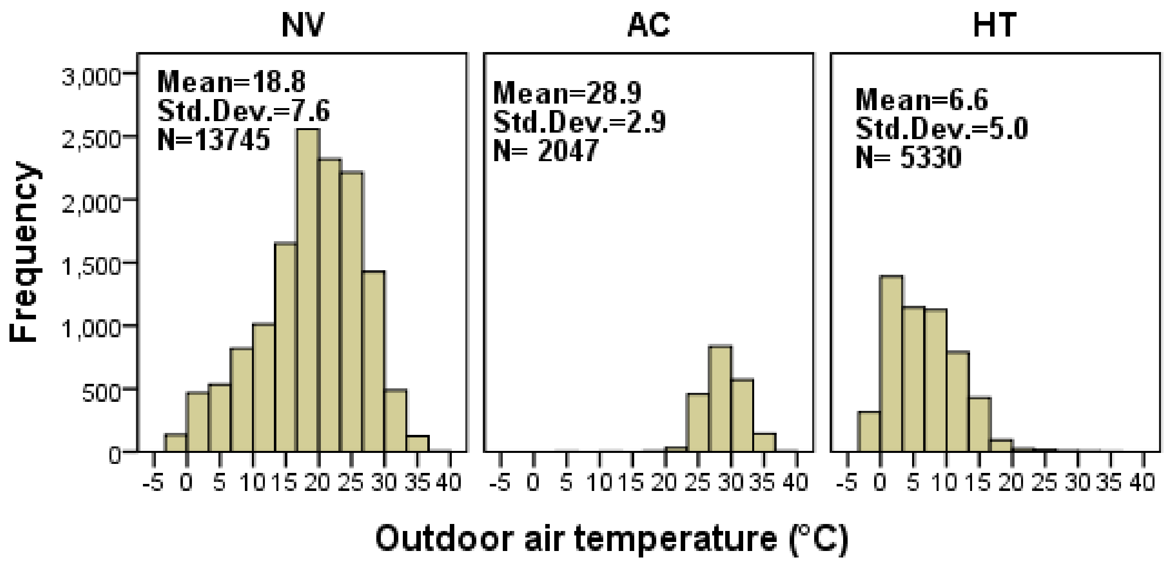

Fig. 4 Distribution of outdoor air temperature during the voting

4.2 Distribution of thermal sensation

In order to clarify the resident's thermal comfort, Fig. 5 shows the distribution of thermal sensation in each mode. Mean thermal sensation vote is 5.0 in NV mode, 5.6 in AC mode and 4.2 in HT mode. Residents feel hot (greater than 5) in AC mode and cold (less than 5) in HT mode. Even though residents used the air conditioning, they are feeling "hot" or "cold". As there are many "5 neutral" votes in NV mode, it can be said that residents are satisfied in the thermal environment of the houses. This may be due to the adaptation of the residents to the local climate and culture.

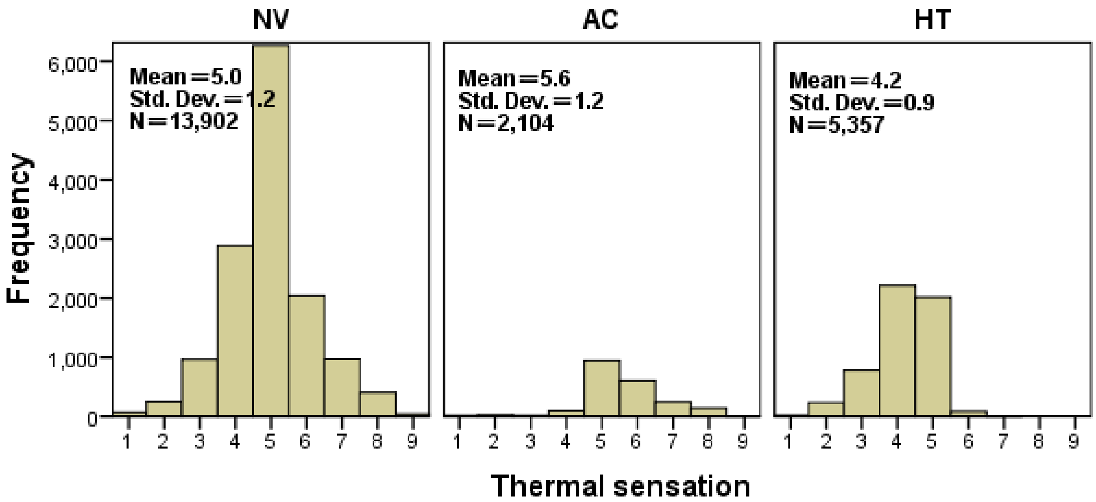

Fig. 5 Distribution of thermal sensation in each mode

4.3 Prediction of comfort temperature by regression method

Regression analysis of the thermal sensation and indoor air temperature is conducted to predict the comfort temperature. Fig. 6 shows the scatter diagram of thermal sensation and indoor air temperature of each mode. The following regression equations are obtained in between the thermal sensation (C) and indoor air temperature (T_i, °C).

NV mode $C=0.149T_i-1.588$ (n=13,471, R^2=0.48, S.E.=0.001, p<0.001) (3)

AC mode $C=0.130T_i-1.946$ (n=1,955, R^2=0.05, S.E.=0.013, p <0.001) (4)

HT mode $C=0.064T_i-3.043$ (n=5,240, R^2=0.10, S.E.=0.003, p<0.001) (5)

Regression coefficient and correlation coefficient of NV mode are higher than AC and HT modes. When the comfort temperature is predicted by substituting "5 neutral" in the equations (3), (4) and (5), it would be 22.8 °C in the NV mode, 23.5 °C in the AC mode and 30.6 °C in the HT mode. The comfort temperature in NV mode is 0.7 °C lower than AC mode. The comfort temperature of the HT mode is considerably high. This might be due to the problem of the regression method as found in the existing research. Thus, the comfort temperature is also predicted using the Griffiths method in next section.

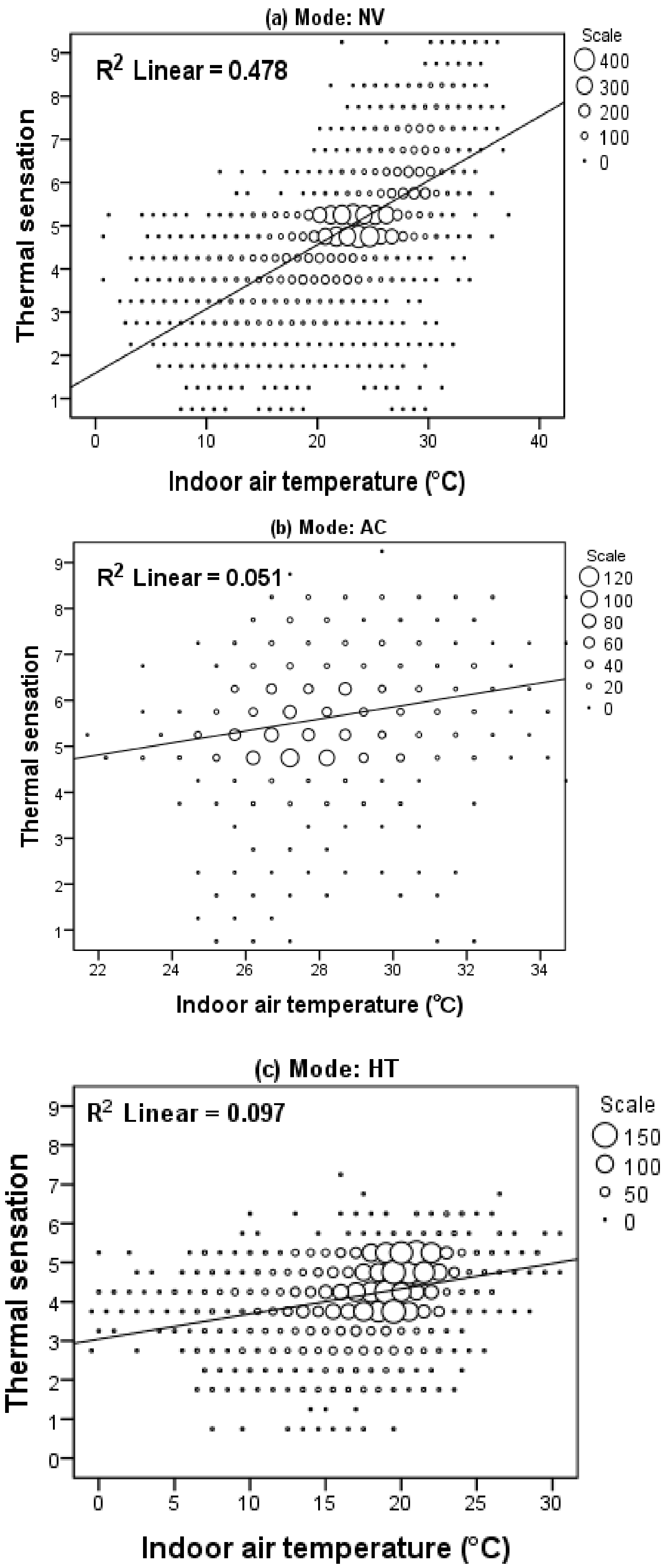

Fig. 6 Relation between the thermal sensation and indoor air temperature

4.4 Prediction of comfort temperature by Griffiths' method

The comfort temperature of the NV, AC and HT modes is further investigated by Griffiths' method. Table 2 and Fig. 7 show the distribution of the comfort temperature which is calculated from each thermal sensation vote and indoor air temperature using Griffiths' method. The comfort temperature is calculated by three regression coefficient of 0.33, 0.44 and 0.67. The mean comfort temperature of each regression coefficient is very similar (Table 2), and thus the comfort temperature which is calculated by 0.67 is used for further analysis.

Mean comfort temperature by the Griffiths' method is 22.7 °C in NV mode, 27.1 °C in AC mode and 18.9 °C in HT mode. When comfort temperature by the regression method and the Griffiths' method are compared, there is no difference in NV mode, but it is 3.6 °C higher in AC mode and 11.7 °C lower in HT mode. Since the mean comfort temperature of the Griffiths' method is close to the mean indoor air temperature, it can be said that the comfort temperature as estimated by the Griffiths' method is more appropriate than the regression method.

Table 2 Comfort temperature predicted by Griffiths' method

Mode	Regression coefficient	Number of sample	Comfort temperature (°C)	
			Mean (°C)	Standard deviation (°C)
NV	0.33	13,472	22.8	4.0
	0.44	13,472	22.8	4.2
	0.67	13,472	22.7	4.5
AC	0.33	1,956	26.2	3.7
	0.44	1,956	26.7	3.0
	0.67	1,956	27.1	2.4
HT	0.33	5,241	20.1	4.2
	0.44	5,241	19.5	4.1
	0.67	5,241	18.9	4.0

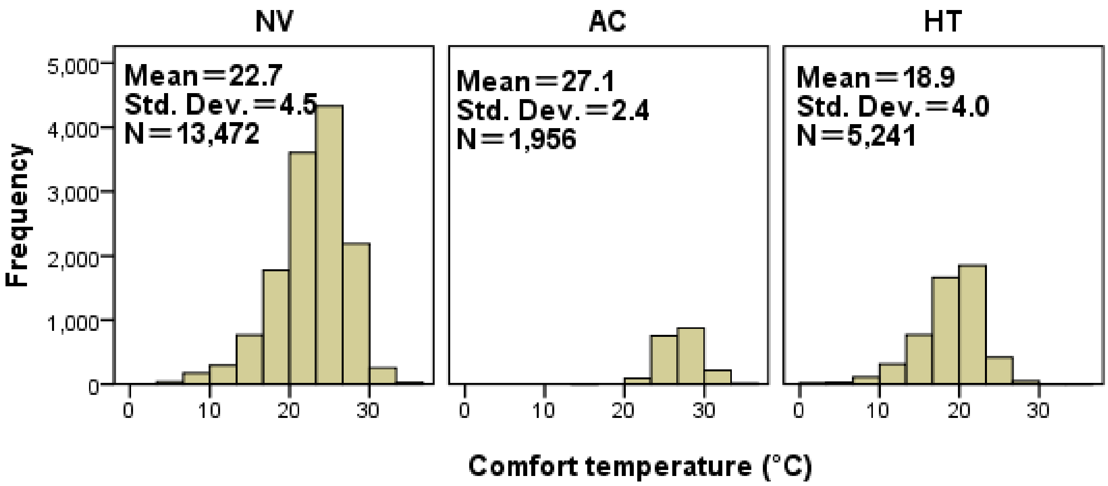

Fig. 7 Prediction of comfort temperature by Griffiths' method in each mode (Regression coefficient = 0.67)

4.5 Seasonal difference in comfort temperature

In this section, to clarify the seasonal difference, the comfort temperature for each month and season is investigated. The comfort temperature of each month and season is shown in Figs. 8 and 9. The comfort temperature of winter or summer months is very similar. However, it is quite different in spring or autumn months. The results showed that the comfort temperature is changes according to the seasonal variation, and thus it is related to the changes in indoor and outdoor air temperature of the spring and autumn. The comfort temperature by the Griffiths' method is 15.6°C in winter, 20.7°C in spring, 26.1°C in summer and 23.6°C in autumn in NV mode. Thus, the seasonal difference of the mean comfort temperature is 10.5K which is similar to the existing research (Rijal et al. 2010, Rijal & Yoshimura 2011).

Table 3 shows a comparison of the comfort temperature obtained in this study with earlier research. We have compared with the NV mode because most of the comfort temperature of the existing research might be from the NV mode. The comfort temperature of the existing research is 21 to 30 ºC which is similar to this research. The results showed that the comfort temperature has regional differences. However, there is only a small difference in comfort temperature in the Kanto (Tokyo) and Kansai (Osaka) areas.

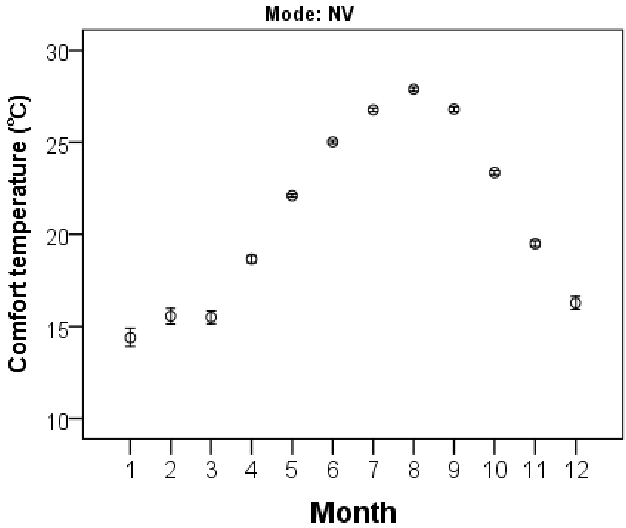

Fig. 8 Monthly mean comfort temperature with 95% confidence intervals predicted by Griffiths' method (Regression coefficient = 0.67)

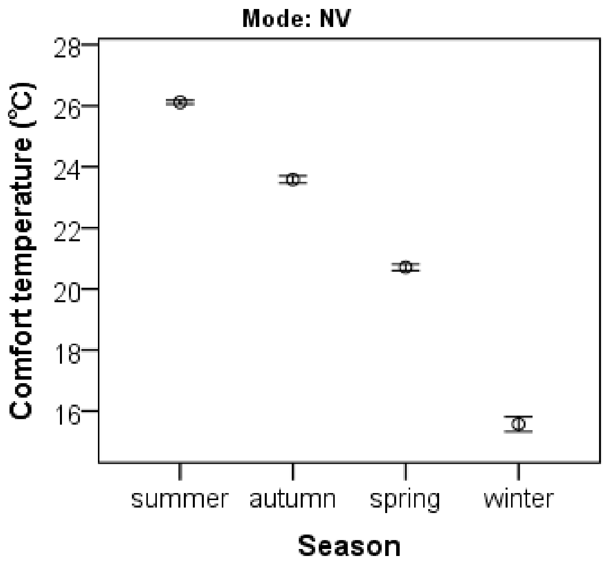

Fig. 9 Seasonal difference of comfort temperature with 95 % confidence intervals by Griffiths' method (regression coefficient = 0.67)

Table 3 Comparison of comfort temperature with existing research

Area	Reference	Season	T_c (°C)
Japan (This study)	This study	summer	26.1
Japan (Kanto)	Rijal & Yoshimura (2011)	summer & autumn	26.2
Japan (Kansai)	Nakaya et al. (2005)	summer	27.6
Nepal	Rijal et al. (2010)	summer	21～30
Pakistan	Nicol etal. (1994), Nicol & Roaf (1996)	summer	26.7～29.9
UK	Rijal & Stevenson (2010)	summer	22.9

C: Thermal sensation, C_m : Mean thermal sensation, T_c : Comfort temperature (℃), T_i : Indoor air temperature (℃) T_{om} : Mean indoor opertive temperature (℃), T_g : Grobe temperature (℃)

4.6 The adaptive model

The adaptive model is a model where the indoor comfort temperature is predicted using the outdoor air temperature (Humphreys 1978, Humphreys & Nicol 1998, ASHRAE 2004, CEN 2007). Table 4 shows the regression equation of the comfort temperature and indoor air temperature for each regression coefficient. The regression coefficient and the correlation coefficient of the NV mode are higher than the AC and HT modes. The coefficient of determination of the regression coefficient of 0.67 is highest for all modes.

The regression coefficient of the CEN Standard is 0.33 in NV mode, it is similar for the regression coefficient of 0.33. In the case of the regression coefficients of 0.44 and 0.67, they are higher than the CEN standard. Since the CEN standard is based on the field investigation in the office buildings, and thus it cannot be compared directly to this research because, residents are fee to adjust the thermal environments at home.

In Table 4, T_{cp} is the predicted indoor comfort temperature using regression equations when the running mean outdoor temperature is 20 °C for NV mode, 28 °C for AC mode and 10 °C for HT mode. Thus, if we know the outdoor temperature, we can predict the indoor comfort temperature.

Figs. 10 & 11 show the relation between the comfort temperature calculated by the Griffiths' method (regression coefficient= 0.67) and the running mean outdoor temperature. The regression equations and given below.

NV mode T_c=0.530T_{rm}+12.5 (n=13,471, R^2=0.68, p<0.001) (6)

AC mode T_c=0.297T_{rm}+18.8 (n=1,955, R^2=0.06, p<0.001) (7)

HT mode T_c=0.307T_{rm}+16.5 (n＝5,240, R^2=0.11, p<0.001) (8)

In HT mode, the variation of comfort temperature is high. In this research, we have also included the Kotatsu (small table with an electric heater underneath and covered by a quilt) in the HT mode, and thus people may find it comfortable at low indoor air temperatures. When a Kotatsu of 90 W (power consumption) is used, there is more than 7 °C thermal comfort effect when room temperature is 11°C (Watanabe et al. 1997). Thus, the comfort range of this research might be high.

Table 4 Regression equations for the adaptive model.

Mode	Regression coefficient	Regression equation	n	R^2	p	T_{cp} (°C)
NV	0.33	T_c=0.361T_{rm}+15.8	13,471	0.40	<0.001	23.0
	0.44	T_c=0.444T_{rm}+14.2	13,471	0.56	<0.001	23.1
	0.67	T_c=0.530T_{rm}+12.5	13,471	0.68	<0.001	23.1
AC	0.33	T_c=0.244T_{rm}+19.5	1,955	0.02	<0.001	26.3
	0.44	T_c=0.270$\mathrm{T_{rm}}$+19.1	1,955	0.03	<0.001	26.7
	0.67	T_c=0.297T_{rm}+18.8	1,955	0.06	<0.001	27.1
HT	0.33	T_c=0.232$\mathrm{T_{rm}}$+18.4	5,240	0.06	<0.001	20.7
	0.44	T_c=0.269T_{rm}+17.5	5,240	0.08	<0.001	20.2
	0.67	T_c=0.307T_{rm}+16.5	5,240	0.11	<0.001	19.6

T_i: Indoor air temperature (°C), T_c: Comfort temperature by Griffiths'method (°C), T_{rm}: Running mean outdoor temperature (°C), n : Number of samples, R^2: Coefficient of determination, P: Significant level of regression coefficient, T_{cp}: Predicted comfort temperature when 20°C (NV), 28°C (AC) and 10°C (HT)

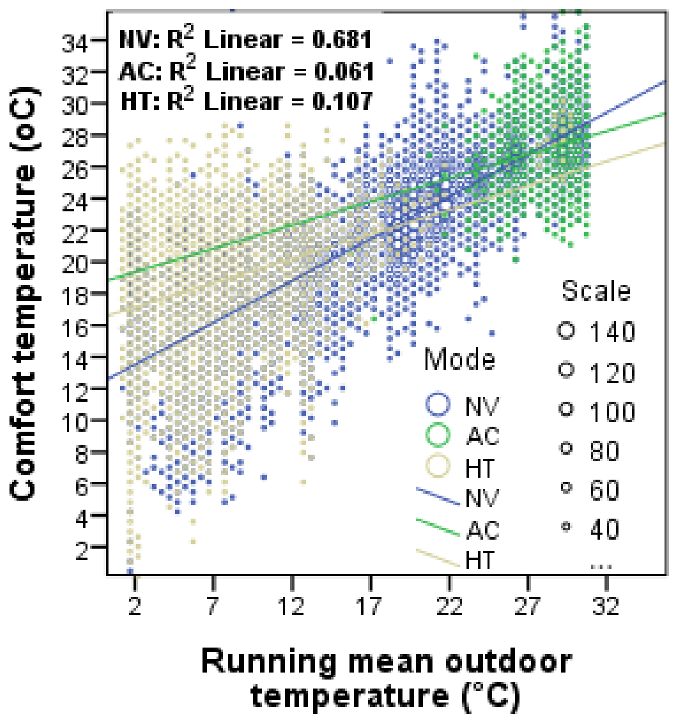

Fig. 10 Relation between the comfort temperature and the running mean outdoor temperature (regression coefficient = 0.67).

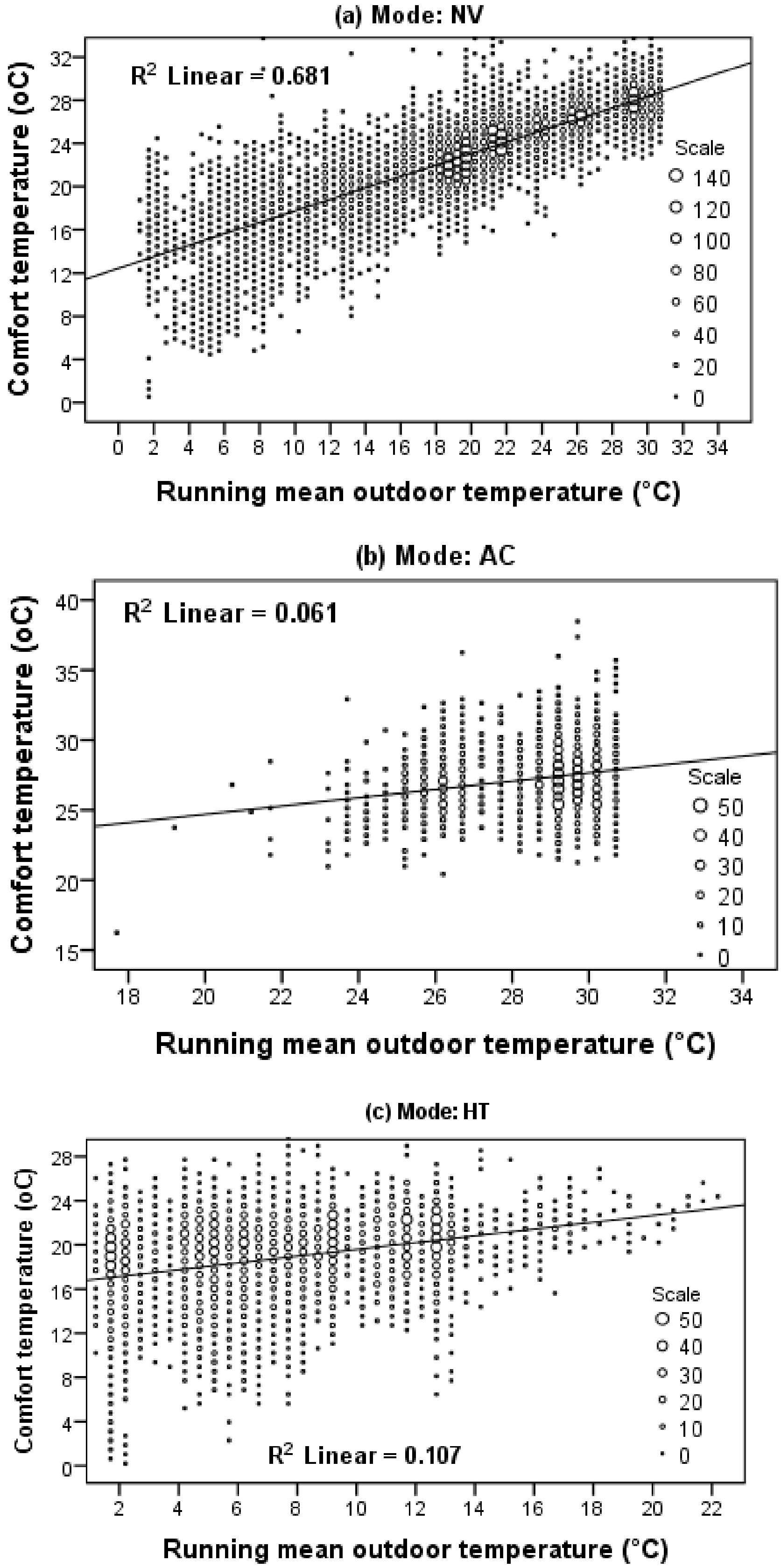

Fig. 11 Relation between the comfort temperature and the running mean outdoor temperature in each mode (regression coefficient = 0.67).

4.7 Comparison with adaptive model

Fig. 12 shows the variation of the comfort temperature in the CEN standard (Nicol & Humphreys 2007). Fig. 13 shows the variation of comfort temperature obtained in this research.

When we compare the regression lines of these two figures, it is very similar in the hot environment (about 25~30 °C). In the previous research, when outdoor running mean temperature is below 12 °C, the comfort temperature is almost constant (Fig. 12). On the other hand, in this research, when outdoor running mean temperature is below 12 °C, the comfort temperature is also gradually decreasing. In the past research, people were not free to adjust the thermal environment in the office buildings, and thus people may not adapt well at low temperatures. In this research, residents are free to adjust the thermal environment in their home, and thus they might be adapting well in the low outdoor temperature compared to the office buildings. However, further research is required for gaining fully acceptable conclusions.

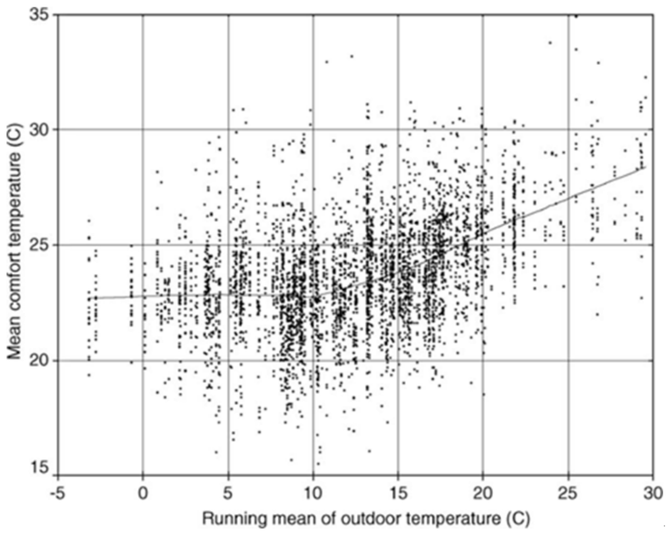

Fig. 12 Variation of the comfort temperature in the CEN standard (Nicol & Humphreys 2007)

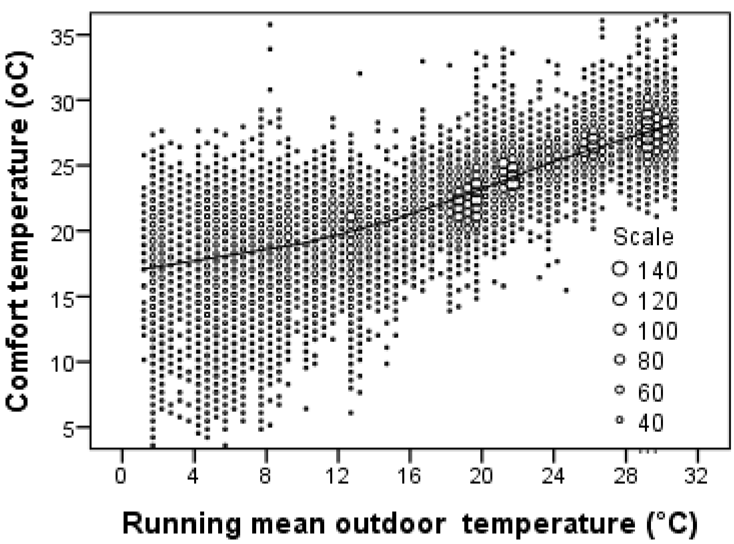

Fig. 13 Variation of the comfort temperature in this research.

5. Conclusions

In this research, we measured the thermal environments in the living rooms and also conducted a thermal comfort survey of the residents and the following results were found:

1. The frequency of "Neutral" vote is highest in the NV mode. It can be said that the residents are highly satisfied with the thermal environment of their homes.
2. The comfort temperature which is predicted by Griffiths' method is 22.8 °C in NV mode, 27.1°C in AC mode and 18.9 °C in HT mode.
3. The comfort temperatures in spring and autumn are very similar. However, the seasonal difference (summer and winter) in comfort temperature is 10.5 K.
4. By using the relationship between indoors and outdoors, the adaptive model was proposed to predict and control the indoor comfort temperature. It can be used in thermal simulation to predict comfort and energy use in building.

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