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Development of the adaptive model for thermal comfort in Japanese houses

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Abstract
This study was undertaken to investigate comfort temperatures and adaptive model in Japanese homes. We measured temperatures in the living rooms and bedrooms, and a thermal comfort survey of residents over a three year in Kanto region of Japan. The residents were found to be highly satisfied with the thermal environment of their houses. Significant seasonal differences were found in their comfort temperatures. The results showed that comfort temperature varied with changes in both the indoor and outdoor climate. The strength of the relationship between indoor and outdoor temperatures justified the adoption of the adaptive model for both prediction and design of control strategies for the provision of indoor comfort.

Keywords: Field survey; Griffiths' method; Comfort temperature; Adaptive model

Introduction
Indoor temperatures are an important factor in creating comfortable homes. An understanding of the locally required comfort temperature can be useful in the design of residences and their heating and cooling systems to avoid excessive energy use.

Comfort temperatures in houses have been widely investigated, with key studies in Japan (Nakaya et al. 2005, Rijal et al. 2013), Nepal (Rijal et al. 2010), Pakistan (Nicol & Roaf 1996) and UK (Rijal & Stevenson 2010). However there are limitations in the research to date with some studies conducted over short time periods, and some based on small samples. Comfort temperatures may also vary according to the month and season, requiring long-term data to fully understand perceptions and behavioural responses to comfort provision in the home.

In 2004 ASHRAE introduced an adaptive standard for naturally ventilated buildings (ASHRAE 2004) and CEN (2007) proposed an adaptive model for free-running naturally ventilated buildings. The adaptive model of thermal comfort was developed largely on the basis of thermal comfort surveys in European and American offices. No Japanese data was included. Occupant behaviour is different in the office and at home, and thus the existing adaptive models may not apply to residences.

There is evidence that people respond differently in their own homes for a number of reasons: social, economic and cultural (Oseland 1995). People at home usually are able to control their own thermal environments, so it may be wondered what is the purpose of knowing what temperatures they choose. Models relating the preferred indoor temperature to the climate are of course of scientific interest as an addition to our knowledge of the results of human adaptive behaviour. They are useful practically too. Knowing what indoor temperatures people are likely to require in winter and in summer helps towards the correct sizing of air conditioning and heating plant – oversized plant is usually less efficient. For the free-running mode of operation the situation is different. The question is then: can this proposed design provide the required indoor temperatures? If thermal simulation or experience suggests that it cannot, then the design can be altered, particularly with regard to window design and thermal mass, so that comfort is more likely to be obtainable. The adaptive relation is a useful design tool.

In order to record seasonal differences in the comfort temperature and to develop a domestic adaptive model for Japanese residences, thermal measurements and a thermal comfort survey were conducted for more than 3 years in the living and bedrooms of residences in the Kanto region of Japan.

Field investigation

A thermal comfort survey and the thermal measurement were conducted in 121 houses in Kanto region (Kanagawa, Tokyo, Saitama and Chiba) of Japan from 2010 to 2013 (Table 1). The detail of surveys 1, 2 and 4 can be found at Rijal, Yoshimura (2011), Katsuno et al. (2012) and Rijal (2013) respectively.

The indoor air temperature and the relative humidity were measured in the living rooms and bedrooms, away from direct sunlight, at ten minute intervals using a data logger (Figure 1). The globe temperature was also measured in the living room in surveys 3, 4 & 5. The number of subjects was 119 males and 124 females. Respondents completed the questionnaire several times a day in the living rooms and twice in the bedroom (“before go to bed” and “after wake-up from the bed”) (Table 2).

The ASHRAE scale is frequently used to evaluate the thermal sensation, but the words “warm” or “cool” imply comfort in Japanese, and thus the SHASE scale (The Society of Heating, Air-Conditioning and Sanitary Engineers of Japan) is also used to evaluate the thermal sensation. To avoid a possible misunderstanding of “neutral”, it is explained as “neutral (neither cold nor hot)” (SHASE scale) or “neutral (neither cool nor warm)” (ASHRAE scale). It is also said that the optimum temperature occurs on the cooler side in summer and on the warmer side in winter (McIntyre 1980, Nakaya et al. 2005). We have collected 32,468 thermal comfort votes. Outdoor air temperature and relative humidity were obtained from the nearest meteorological station.

Table 1. Description of survey

Survey	Survey period		Surveyed room	Measured variables*	Number of houses	Number of subjects			Number of votes	
	Start date	End date				Male	Female	Total	Living room	Bedroom
1	06-7-2010	18-7-2011	Living, Bed	T_i, RH_i	11	16	14	30	3299	2558
2	05-8-2011	06-9-2011	Living	T_i, RH_i	55	52	57	109	2819	-
3	21-7-2011	08-5-2012	Living, Bed	T_i, RH_i, T_g	14	11	12	23	463	984
4	25-7-2012	24-6-2013	Living, Bed	T_i, RH_i, T_g	30	26	28	54	13083	7061
5	10-8-2013	03-10-2013	Living, Bed	T_i, RH_i, T_g	11	14	13	27	936	1265

T_i: Indoor air temperature (°C), RH_i: Indoor relative humidity (%), T_g: Indoor globe temperature (°C), *: T_g is measured only in the living room.

Table 2. Questionnaires for thermal comfort survey

No.	SHASE scale	ASHRAE scale	Thermal preference
	Now, how do you feel the air temperature?	Now, how do you feel the air temperature?	Now, how do you prefer the air temperature?
1	Very cold	Cold	Much warmer
2	Cold	Cool	A bit warmer
3	Slightly cold	Slightly cool	No change
4	Neutral (neither cold nor hot)	Neutral (neither cool nor warm)	A bit cooler
5	Slightly hot	Slightly warm	Much cooler
6	Hot	Warm	
7	Very hot	Hot	

Figure 1 Details of the thermal measurement

Results and discussion

The data were divided into three groups: the FR mode (free running), CL mode (cooling by air conditioning) and HT mode (heating). First we have determined the CL and HT modes based on actual cooling and heating used. Some in these categories used window opening to provide ventilation. Then, all the other data were classified as being in the FR mode. In previous research, the data is divided into two modes: free running and heated/cooled (CIBSE 2006, CEN 2007) or NV and HVAC building in the classification used in ASHRAE standard 55-2004. However, the CL and HT modes are two distinct groups of data (generally CL used in summer and HT is used in winter), and need to be analysed separately.

Distribution of outdoor and indoor temperature

The mean outdoor air temperatures during the voting were 19.5 °C, 27.6 °C and 7.2 °C for FR, CL and HT modes respectively (Figure 2). The mean indoor air temperatures during the voting were 24.2 °C, 27.3 °C and 19.2 °C for FR, CL and HT modes respectively. The Japanese government recommends the indoor temperature settings of 20 °C in winter and 28 °C in summer respectively. The results showed that the mean indoor temperatures during heating and cooling were close to the recommendation. The mean indoor and outdoor temperature difference was 4.7 K, -0.3 K and 12.0 K for FR, CL and HT modes respectively. The results show that the seasonal difference of the indoor air temperature is quite large, and that the data represent a wide range of outdoor temperature.

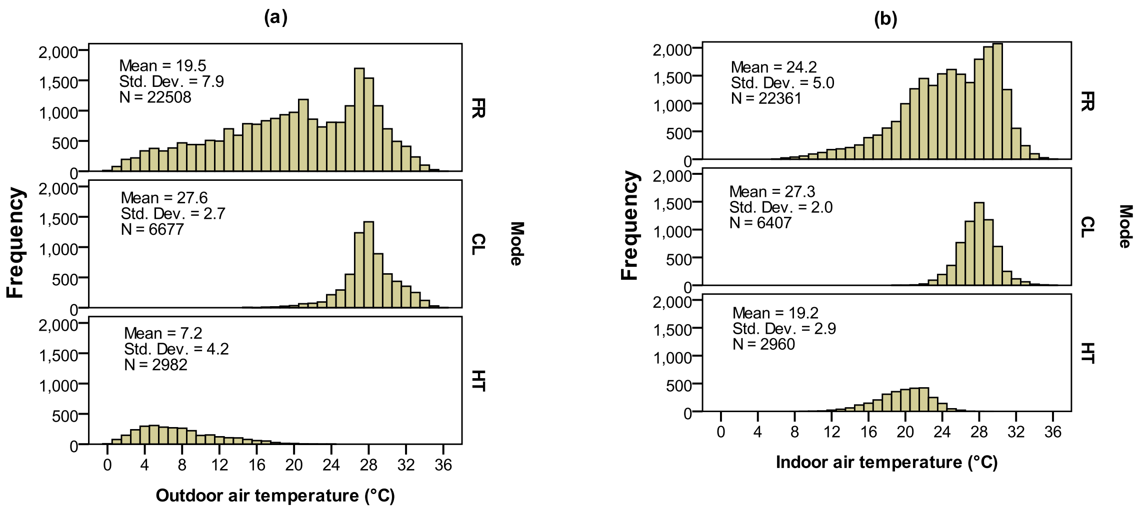

Figure 2 Distribution of outdoor and indoor air temperature in various modes.

Comparison of the scales

We have analysed the performance of ASHRAE and SHASE scales by regressing the thermal response on the indoor air temperature, using the data collected from people in their living rooms and bedrooms. Table 3 compares the relevant regression statistics.

It is apparent that the thermal sensation when expressed on the SHASE scale correlates much more closely with the indoor air temperature than it does when expressed on the ASHRAE scale. It also has a smaller residual standard deviation, which indicates that people agree more closely on their sensation at any particular temperature (their responses are more similar) when this scale is used. The regression coefficients are similar on the two scales. It can be concluded that the SHASE scale is superior for these data, and should be used to present the results.

The preference scale has fewer categories (5 rather than 7) and so its regression coefficient and residual standard deviation are not directly comparable with the seven-category scales. Its correlation with temperature is quite high at 0.62. Its purpose is different from that of the SHASE scale, and so it should be retained.

Table 3 Regression analysis of thermal sensation and thermal preference

Scale	Number of votes	Regression coefficient/K	Correlation coefficient	Residual standard deviation	Overall standard deviation of thermal sensation
ASHRAE	21,045	0.130	0.485	1.066	1.219
SHASE	31,749	0.113	0.616	0.704	0.894
Preference	29,293	0.092	0.617	0.563	0.716

Distribution of thermal sensation

Mean thermal sensation vote was 4.1 in FR mode, 4.2 in CL mode and 3.5 in HT mode. Residents sometimes felt hot (greater than 4) in CL mode and sometimes felt cold (less than 4) in HT mode (Table 4). Even though residents used the heating or cooling, they sometimes felt "cold" or "hot". As there are many "4 neutral" votes in FR mode, it can be said that residents were generally satisfied in the thermal environment of the houses. This may be due to the adaptation of the residents to the local climate and culture.

Table 4 Percentage of thermal sensation in each mode

Mode	Items	Thermal sensation							Total
		1	2	3	4	5	6	7	
FR	N	93	907	3,532	12,757	3,776	1,323	281	22,669
	Percentage (%)	0.4	4.0	15.6	56.3	16.7	5.8	1.2	100
CL	N	13	52	514	4,639	1,226	245	60	6,749
	Percentage (%)	0.2	0.8	7.6	68.7	18.2	3.6	0.9	100
HT	N	54	357	757	1,836	46	-	-	3,050
	Percentage (%)	1.8	11.7	24.8	60.2	1.5	-	-	100

N: Number of sample

Prediction of the comfort temperature

Regression method

Regression analysis of the thermal sensation and indoor air temperature was conducted to predict the comfort temperature (Figure 3). The following regression equations are obtained for the thermal sensation (C) and indoor air temperature (T_i, °C).

FR mode $C=0.123T_i+1.11$ ($n=22{,}346$, $R^2=0.44$, S.E.$=0.001$, $p<0.001$) (1)

CL mode $C=0.091T_i+1.66$ ($n=6{,}400$, $R^2=0.07$, S.E.$=0.004$, $p<0.001$) (2)

HT mode $C=0.103T_i+1.50$ ($n=2{,}900$, $R^2=0.14$, S.E.$=0.005$, $p<0.001$) (3)

n: Number of sample, R^2: Coefficient of determination, S.E.: Standard error of the regression coefficient, p: Significant level of regression coefficient.

The regression coefficient and correlation coefficient for the FR mode are higher than for the CL and HT modes. When the comfort temperature is predicted by substituting "4 neutral" in the equations (1) to (3), it would be 23.5 °C in the FR mode, 25.7 °C in the CL mode and 24.3 °C in the HT mode. The comfort temperature of the HT mode is unrealistically high. 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 (Rijal et al. 2013). So to avoid the problem the comfort temperature is estimated using the Griffiths method in next section.

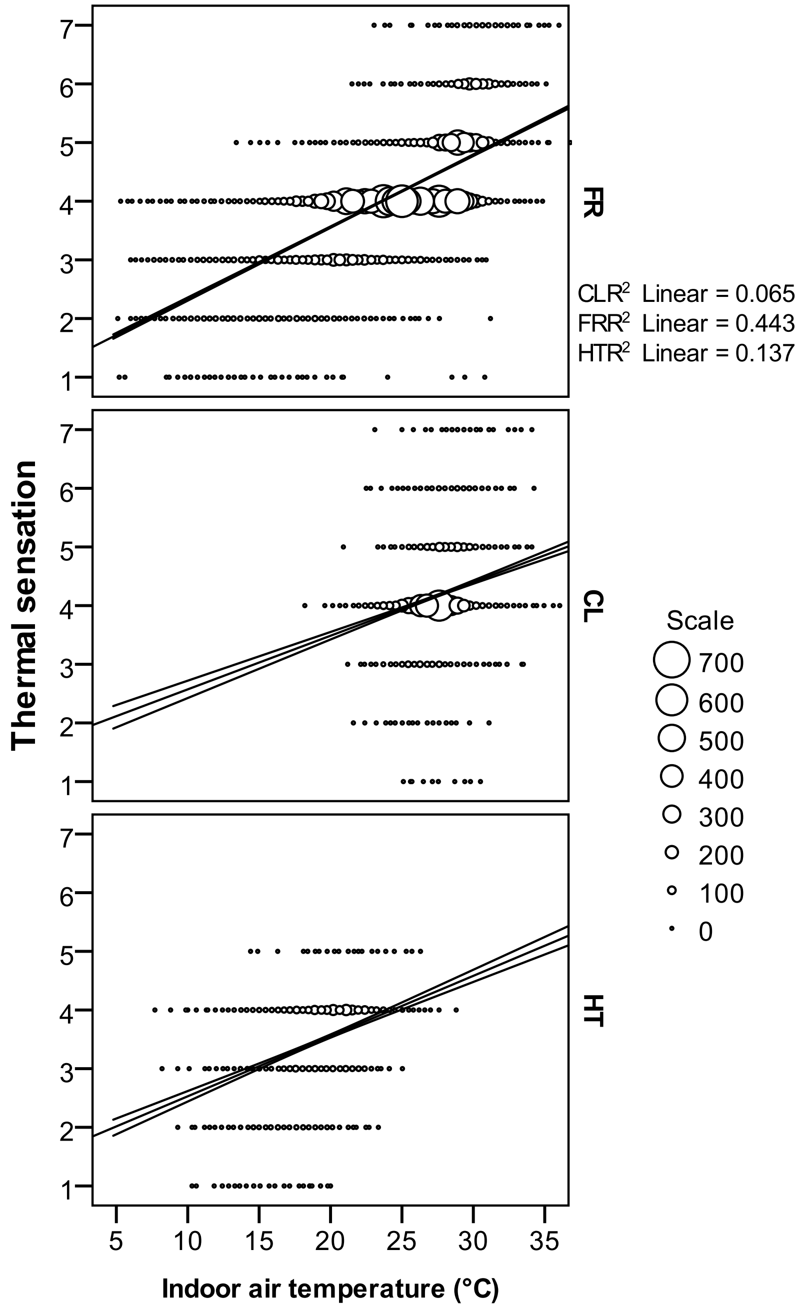

Figure 3 Relation between the thermal sensation and indoor air temperature

Griffiths' method

The comfort temperature is predicted by the Griffiths' method (Griffiths 1990, Nicol et al. 1994, Rijal et al. 2008).

$$T_c = T_i + (4 - C) / a \qquad (4)$$

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

In applying the Griffiths' method, Nicol et al. (1994) and Humphreys et al. (2013) used the constants 0.25, 0.33 and 0.50 for a 7 point thermal sensation scale. We have also investigated the comfort temperature using these regression coefficients. The mean comfort temperature with each coefficient is similar (Table 5), so it matters little which coefficient is adopted. The comfort temperature calculated with the coefficient 0.50 is used for further analysis.

The mean comfort temperature by the Griffiths' method is 24.1 °C in FR mode, 27.0 °C in CL mode and 20.2 °C in HT mode (Figure 4). We chose to use the Griffiths method because in the presence of adaptation ordinary regression can give misleading values for the comfort temperatures. In our data powerful adaptation to the seasonal variation of indoor temperature necessitates the use of the Griffiths method.

Table 5 Comfort temperature predicted by Griffiths' method

Mode	Regression coefficient	Number of sample	Comfort temperature (°C)	
			Mean (°C)	Standard deviation (°C)
FR	0.25	22,346	23.9	3.8
	0.33	22,346	24.0	3.8
	0.50	22,346	24.1	4.0
CL	0.25	6,400	26.7	3.0
	0.33	6,400	26.8	2.5
	0.50	6,400	27.0	2.1
HT	0.25	2,960	21.3	3.4
	0.33	2,960	20.8	3.0
	0.50	2,960	20.2	2.7

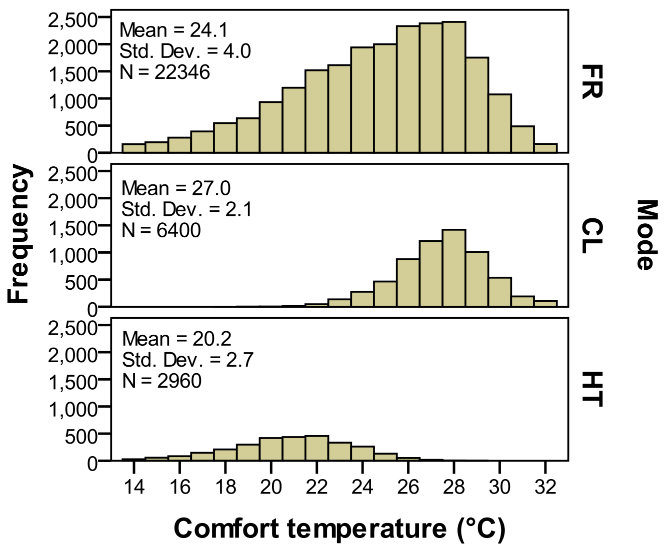

Figure 4 Prediction of comfort temperatures from each observation by Griffiths' method in each mode

Seasonal difference in comfort temperature

In this section, to clarify the seasonal difference, the comfort temperature for each month and season is investigated (Figures 5 and 6). The comfort temperature does not vary much within the winter or summer seasons. However, it is quite changeable in the spring and autumn. The results showed that the comfort temperature changes according to the season, and thus it is related to the changes in indoor and outdoor air temperature which occur in spring and autumn. The comfort temperature by the Griffiths' method is 18.1 °C in winter, 21.9 °C in spring, 27.1 °C in summer and 24.3 °C in autumn in FR mode. Thus, the seasonal difference of the mean comfort temperature is 9.0 K which is similar to the value found in previous research (Rijal et al. 2010 & 2013). The comfort temperature of the heating HT mode also changes significantly from season to season (Figure 6).

We have compared the comfort temperatures from the FR mode with the values from previous research, which were probably also chiefly from this mode (Table 6). The comfort temperature found in previous research ranges from 8.4 to 30.0 ºC. The wider range may suggest that the comfort temperature has regional differences.

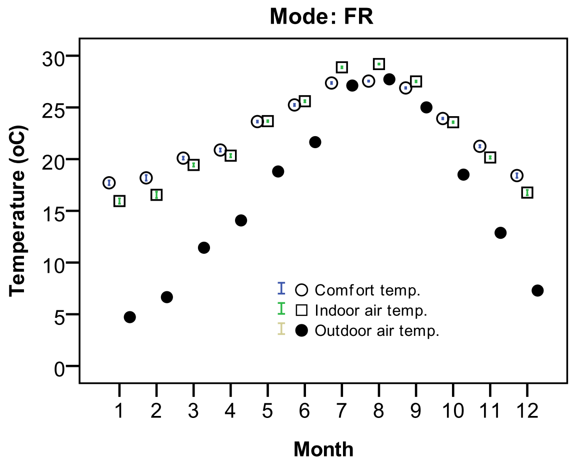

Figure 5 Monthly mean comfort temperature with 95% confidence intervals predicted by Griffiths' method

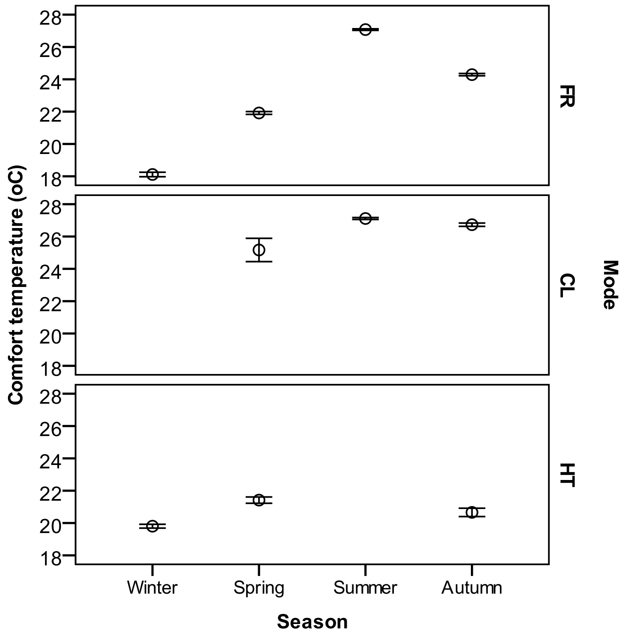

Figure 6 Seasonal difference of comfort temperature with 95 % confidence intervals by Griffiths' method

Table 6 Comparison of comfort temperature with previous research

Area	Reference	Comfort temperature (°C)			
		Winter	Spring	Summer	Autumn
Japan (Kanto)	This study (FR mode)	18.1	21.9	27.1	24.3
Japan (Gifu)	Rijal et al. (2013)	15.6	20.7	26.1	23.6
Japan (Kansai)	Tobita et al. (2007)	9.9~10.9	-	-	-
Japan (Kansai)	Nakaya et al. (2005)	-	-	27.6	-
Nepal	Rijal et al. (2010)	13.4~24.2	-	21.1~30.0	-
Nepal	Rijal & Yoshida (2006)	8.4~12.9	-	-	-
Pakistan	Nicol & Roaf (1996)	19.8~25.1	-	26.7~29.9	-
UK	Rijal & Stevenson (2010)	19.4	19.7	22.9	21.3

The adaptive model

Running mean outdoor temperature

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

$$T_{rm} = \alpha T_{rm-1} + (1-\alpha)T_{od-1} \quad (5)$$

Where, T_{rm-1} is the running mean outdoor temperature for the previous day (°C), T_{od-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.

Linear regression equations

An adaptive model relates the indoor comfort temperature to the outdoor air temperature (Humphreys 1978, Humphreys & Nicol 1998, ASHRAE 2004, CEN 2007). Figure 7 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=0.453T_{rm}+15.0 (n=22,346, R^2=0.68, S.E.=0.002, p<0.001) (6)
CL mode T_c=0.188T_{rm}+21.9 (n=6,400, R^2=0.03, S.E.=0.014, p<0.001) (7)
HT mode T_c=0.178T_{rm}+18.8 (n＝2,960, R^2=0.05, S.E.=0.014, p<0.001) (8)

T_c: Comfort temperature by Griffiths' method (°C), T_{rm}: the exponentially-weighted running mean outdoor temperature for the day (°C). (S.E. is the standard error of the regression coefficient.)

The regression coefficient and the correlation coefficient in the FR mode are higher than in the CL and HT modes. The regression coefficient in the FR mode is higher than that in the CEN standard (=0.33). The CEN standard is based on the field investigation in the office buildings, and therefore may not apply to dwellings, where residents have more freedom to adapt. For example, when the running mean outdoor temperature is 25 °C, 28 °C and 10 °C, the comfort temperature would be 26.3 °C, 27.2 °C and 20.6 °C for the FR, CL and HT modes respectively.

In the 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). This may account for the wide range of comfort temperatures found in this research.

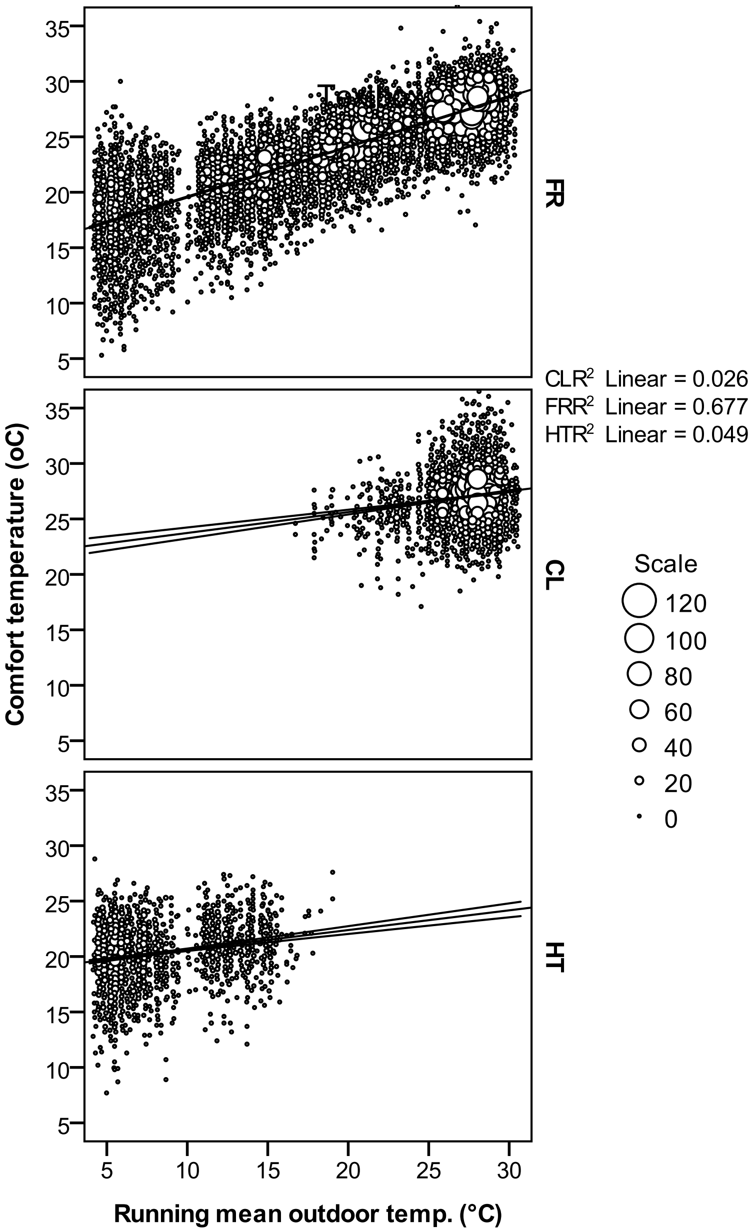

Figure 7 Relation between the comfort temperature and the running mean outdoor temperature in each mode

Comparison with adaptive model

Figure 8 shows the variation of the comfort temperature in the CEN standard (Nicol & Humphreys 2007), Japanese houses (Rijal et al. 2013) and in this research. When we compare the regression lines of these three figures, it is very similar in the hot environment (about 25~30 °C). In the European research, when outdoor running mean temperature is below 12 °C, the comfort temperature is almost constant (Figure 8 (a)). On the other hand, in the Japanese houses, when outdoor running mean temperature is below 12 °C, the comfort temperature is also gradually decreasing. In the research in European offices, people might not be so free to adjust the thermal environment, 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.

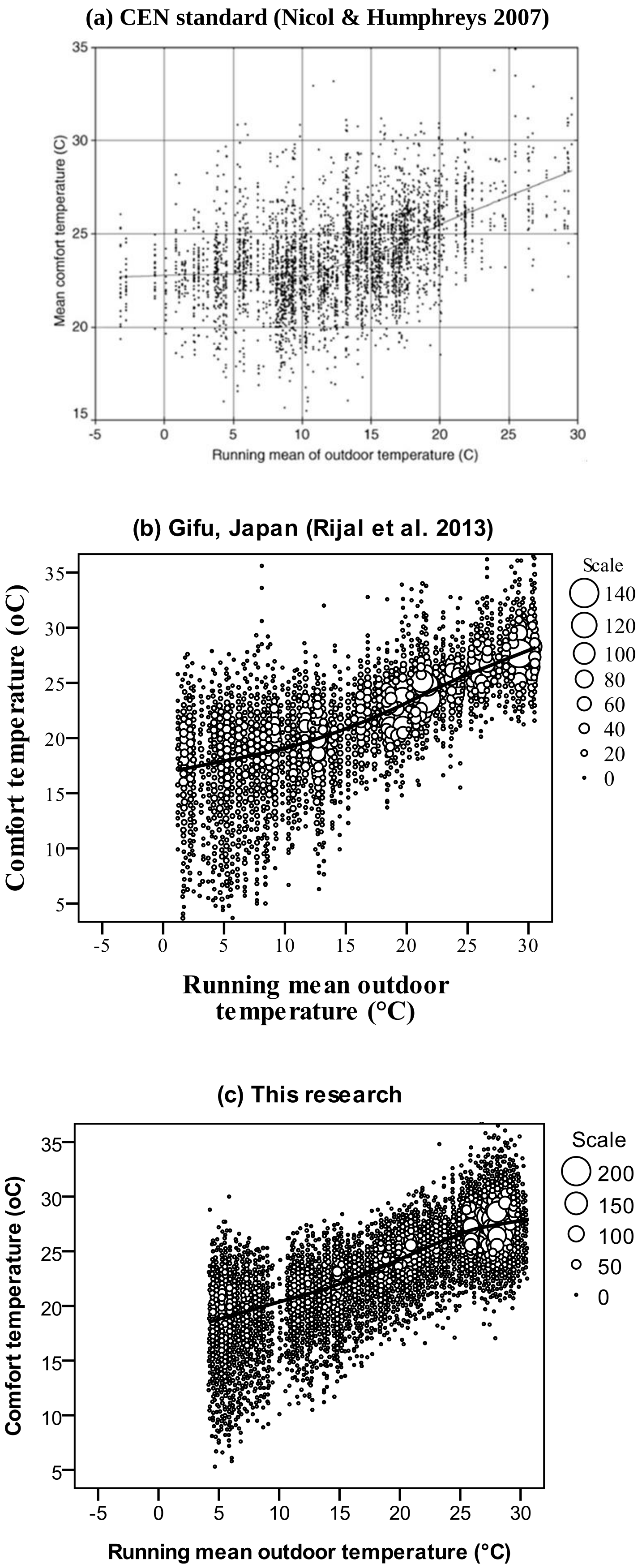

Figure 8 Variation of the comfort temperature in previous and this research.

Conclusions

A thermal comfort survey of the residents of the Kanto region of Japan was conducted over three years. The thermal environment in living rooms and bedrooms were investigated. The following results were found:

1. The residents proved to be highly satisfied with the thermal environment of their homes, as indicated by the high proportion of 'neutral' responses.
2. The average comfort temperature was 27.0 °C when cooling was used, 20.2 °C when heating was used, and 24.1 °C when neither heating nor cooling were used (the FR mode).
3. The comfort temperatures in spring and autumn were very similar. The seasonal difference (summer and winter) in comfort temperature was very high at 9.0 K.
4. An adaptive relation between the comfort temperature indoors and the outdoor air temperature could be an effective tool for predicting comfort temperature and for informing control strategies.

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