Field Investigation of Comfort Temperature and Adaptive Model in Japanese Houses

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ABSTRACT: In order to clarify the comfort temperature and to investigate the adaptive model in Japanese houses, we have conducted the thermal comfort survey in 30 living rooms for summer in Kanto region of Japan. We collected 3991 votes from 52 subjects. The comfort temperature was predicted by Griffiths' method and compared with CEN standard. The logistic regression analysis was conducted to predict the occupant behaviour. We have found the following results.

1. *The residents are highly satisfied with the thermal environment of their houses.*
2. *The comfort temperature in naturally ventilated mode is 27.6±1.8 °C in summer. The results showed that people are highly adapted in the thermal condition of the houses, and thus the thermal comfort zone is wider than the conventional standard.*
3. *The comfort temperature of this study is within the acceptable zone of the CEN standard.*
4. *The residents adapt in the hot environments using behavioural adaptation such as window opening and fan use.*

Keywords: houses, thermal comfort survey, comfort temperature, adaptive model

INTRODUCTION

The basic need for human being for survival is "food, clothing and housing". People tend to choose the most comfortable and favorable of these items available during their life. People also want to buy and live in a comfortable home, which normally represents their most significant expenditure in their lifetime. Thus, it is highly important to build a very comfortable home to fulfill this desire of the average person.

It is thought that thermal comfort is one of the most important factors in creating the most comfortable homes. By investigating the comfort temperature of the residents, it can be used as a customary temperature of the house to minimize the excessive energy use and save the overall energy cost of the household. So far, there are many researches about the comfort temperature of the houses in Japan [1 ~ 5], Nepal [6], Pakistan [7, 8] and UK [10]. However, some researches are conducted only for a short period of time, and some offer only a few samples.

In order to clarify the comfort temperature and investigate the adaptive model in Japanese houses, we have conducted the thermal comfort survey in 30 living rooms for summer in Kanto region of Japan.

FIELD INVESTIGATION

The indoor air temperature, the globe temperature and the relative humidity were measured in the living room, avoiding the direct sunlight, at ten minute intervals using a data logger. The number of subjects was 25 males and 27 females. The thermal comfort survey was conducted from 25 July to 17 September 2012 several times a day using 7 point thermal sensation scale and 5 point thermal sensation scale (Figs. 1 & 2). Even though the ASHRAE scale is frequently used to evaluate the thermal sensation, the words "warm" or "cool" imply comfort in Japanese, and thus the SHASE (The Society of Heating, Air-Conditioning and Sanitary Engineers of Japan) scale is also used to evaluate the thermal sensation. To avoid the possible misunderstanding of the "neutral" in the thermal sensation scale, it is explained as "neutral (neither cold nor hot)" or "neutral (neither cool nor warm)". It is also said that the optimum temperature occurs on the cooler side in summer and on the warmer side in winter [1, 10]. The occupant behaviour in the living room was recorded in binary form several times a day (0 = window closed or cooling off or fan off, 1 = window open or cooling on or fan on). We collected 3991 votes. Outdoor air temperature and relative humidity were obtained from the nearest meteorological station.

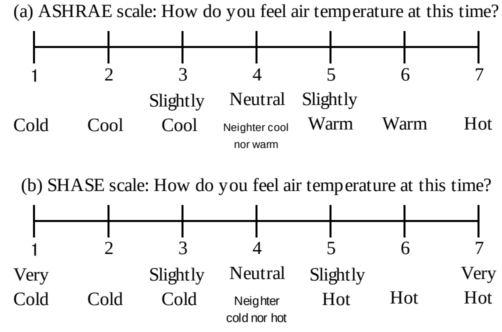

Figure 1: Thermal sensation scale.

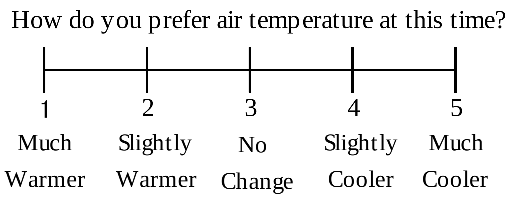

Figure 2: Thermal preference scale.

RESULTS AND DISCISSIONS

The data were divided into two groups: the NV mode (naturally ventilated) and AC mode (cooling by air conditioning). First, we have determined the AC mode based on actual cooling and heating used. Then, all the other data were classified as being in the NV mode. So, strictly speaking, the NV mode is the 'free running' mode where the cooling is not being used to control the indoor environment [11].

RESULTS AND DISCISSIONS

Fig. 3 shows the monthly mean temperature in NV and AC modes. Table 1 shows the correlation coefficient in NV and AC modes.

Due to a high correlation coefficient, the monthly mean indoor and globe temperature is very similar in NV and AC mode. In NV mode, indoor temperatures are higher than the outdoor air temperature. However in AC mode, the indoor temperatures are lower than the outdoor air temperature except in September. The Japanese government recommends the indoor temperature settings of 28 °C in summer. The results showed that the mean indoor temperature setting in AC mode was similar to the recommendation.

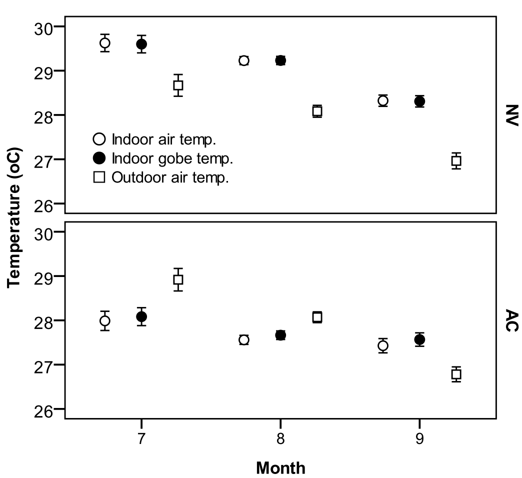

Figure 3: Monthly mean indoor temperature, indoor globe temperature and outdoor air temperature in NV and AC modes during the voting.

Table 1: Correlation coefficient in NV and AC modes.

Mode	Items	$T_i : T_o$	$T_g : T_o$	$T_i : T_g$
NV	r	0.57	0.57	0.98
	N	1,860	1,915	1,860
AC	r	0.22	0.20	0.89
	N	1,805	2,076	1,805

T_i: Indoor air temp. (°C), T_g: Indoor globe temp. (°C), T_o: Outdoor air temp. (°C), $p<0.001$, p: Significant level, r: Correlation coefficient, N: Number of sample

DISTRIBUTION OF THERMAL SENSATION

Table 2 shows the correlation coefficient of the thermal sensation and thermal preference or temperatures. The correlation coefficient of the SHASE scale and thermal preference is higher than the ASHRAE scale and thermal preference. The SHASE scale is better correlated with the indoor air temperature and globe temperature. Thus, we have used the SHASE scale for further analysis.

Mean thermal sensation vote was 4.7 in NV mode, 4.3 in AC mode. Even though residents used the cooling, they sometimes felt "hot". The proportion of people voting in the thermal comfort zone (votes 3, 4 & 5) in the NV and AC modes is 84% and 97% (Table 3).

It can be said that residents were generally satisfied in the thermal environment of their houses. This may be due to the thermal adaptation of the residents to the local climate and culture.

Table 2: Correlation coefficient with ASHRAE and SHASE scales

Mode	Items	ASHRAE			SHASE		
		TP	T_i	T_g	TP	T_i	T_g
NV	r	0.73	0.36	0.36	0.81	0.38	0.37
	N	1,915	1,860	1915	1,915	1860	1915
AC	r	0.77	0.30	0.28	0.86	0.35	0.32
	N	2,076	1,805	2076	2,076	1805	2076

TP: Thermal preference, T_i: Indoor air temp. (°C), T_g: Globe temp. (°C), $p<0.001$, p: Significant level, r: Correlation coefficient, N: Number of sample

Table 3: Correlation coefficient in NV and AC modes

Mode	Items	Thermal sensation 1	2	3	4	5	6	7	Total
NV	N	1	-	24	904	685	253	48	1,915
	P (%)	0.1	-	1.3	47.2	35.8	13.2	2.5	100
AC	N	2	5	152	1284	569	58	6	2,076
	P (%)	0.1	0.2	7.3	61.8	27.4	2.8	0.3	100

N: Number of sample, P: Percentage

PREDICTION OF COMFORT TEMPERATURE BY REGRESSION METHOD

Regression analysis of the thermal sensation and indoor air temperature was conducted to predict the comfort temperature (Fig. 4). The following regression equations are obtained for the thermal sensation (C) and indoor air temperature (T_i, °C) or globe temperature (T_g, °C).

NV mode

$$C=0.192T_i-0.872 \text{ (n=1860, } R^2=0.14, p<0.001) \quad (1)$$

$$C=0.189T_g-0.809 \text{ (n=1915, } R^2=0.14, p<0.001) \quad (2)$$

AC mode

$$C=0.125T_i+0.705 \text{ (n=1805, } R^2=0.12, p<0.001) \quad (3)$$

$$C=0.134T_g+0.523 \text{ (n=2076, } R^2=0.11, p<0.001) \quad (4)$$

n: Number of sample, R^2: Coefficient of determination, p: Significant level of regression coefficient.

The regression coefficient for the NV mode is higher than that of the AC. When the indoor or globe comfort temperature is predicted by substituting "4 neutral" in the equations (1) to (4), it would be 25.4 °C in the NV mode and 26.4 °C or 25.9 °C in the AC mode.

As shown in the figure, the comfort temperature is predicted around the few data points, and thus linear model is not suitable to predict the comfort temperature. 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 [5, 6]. So to avoid this problem the comfort temperature is estimated using the Griffiths method in next section.

PREDICTION OF COMFORT TEMPERATURE BY GRIFFITHS METHOD

The comfort temperature is predicted by the Griffiths' method [7, 12, 13].

$$T_c = T + (4 - C) / a \quad (5)$$

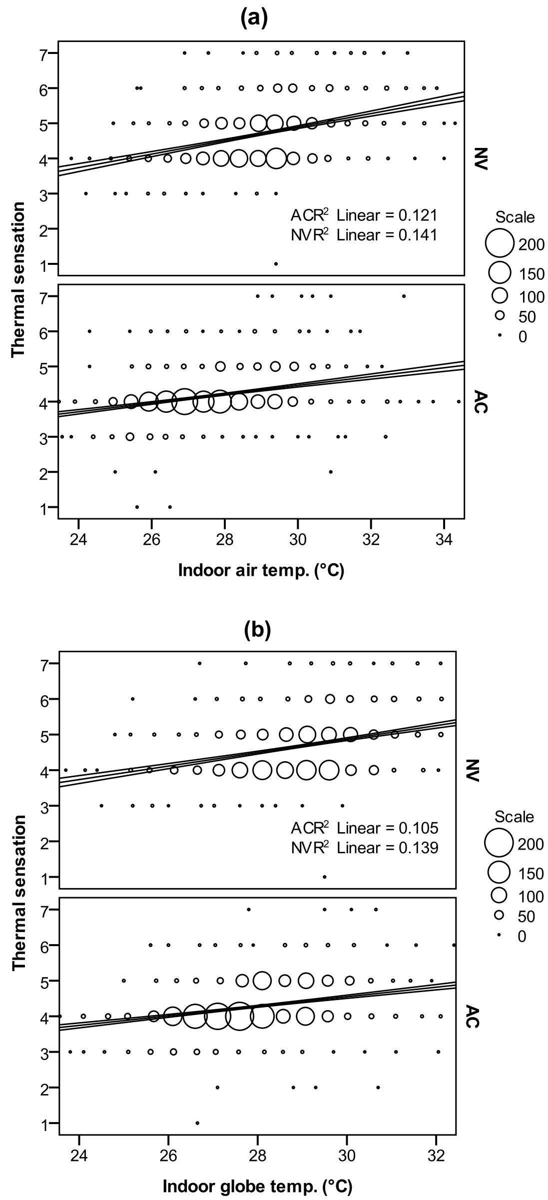

Figure 4: Relation between the thermal sensation and the temperature.

T_c: The comfort temperature by Griffiths' method (°C), T: Indoor air temperature or globe temperature (°C), C: Thermal sensation vote, a: The rate of change of thermal sensation with room temperature.

In applying the Griffiths' method, Nicol et al. [7] and Humphreys et al. [14] 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 not very different (Table 4), 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 air or globe temperature by the Griffiths' method is 27.6 °C in NV mode and 27.3 °C in AC mode (Fig. 5). Since the mean comfort temperature of the Griffiths' method is comparable to the indoor air and globe temperature when voting "4 neutral" (Table 5). It is probable that the comfort temperature as estimated by the Griffiths' method is more appropriate.

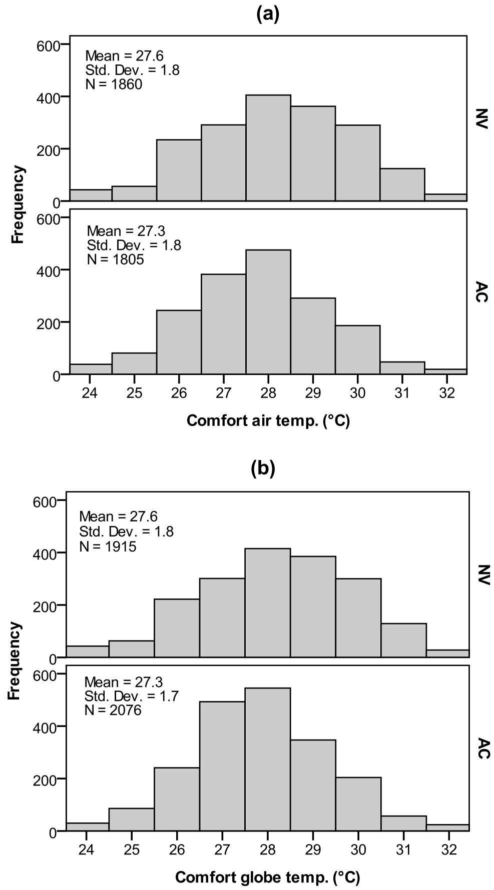

Figure 5: Comfort temperature predicted by Griffiths method.

Table 4: Comfort temperature predicted by Griffiths' method

Mode	RC	T_{ci} (°C)			T_{cg} (°C)		
		N	Mean	SD	N	Mean	SD
NV	0.25	1,860	26.2	3.1	1,915	26.3	3.0
	0.33	1,860	26.9	2.4	1,915	26.9	2.4
	0.50	1,860	27.6	1.8	1,915	27.6	1.8
AC	0.25	1,805	26.9	2.5	2,076	26.8	2.6
	0.33	1,805	27.1	2.1	2,076	27.0	2.1
	0.50	1,805	27.3	1.8	2,076	27.3	1.7

RC: Regression coefficient, T_{ci}: Comfort indoor temp., T_{cq}: Comfort globe temp., N: Number of sample, SD: Standard deviation

Table 6 shows a comparison of the comfort temperature obtained in this study with existing research. The comfort temperature of the existing research is similar to this research (Table 6).

Table 5: Indoor air temperature and globe temperature when voting "4. Neutral".

Mode	Items	N	Mean (°C)	SD (°C)
NV	T_i	851	28.5	1.5
	T_g	904	28.5	1.5
AC	T_i	1,264	27.4	1.7
	T_q	1,284	27.6	1.6

T_i: Indoor air temp., T_g: Indoor globe temp., SD: Standard deviation

Table 6: Comparison of comfort temperature with existing research in summer.

Area	Reference	T_c (°C)
Japan (Kanto)	This study (NV mode)	27.6*
Japan (Gifu)	Rijal et al. [5]	26.1
Japan (Kanto)	Katsuno et al. [4]	27.6
Japan (Kanto)	Yoshimura et al. [2]	29
Japan (Kanto)	Rijal & Yoshimura [3]	27.2*
Japan (Kansai)	Nakaya et al. [1]	27.6
Nepal	Rijal et al. [6]	21.1~30.0
Pakistan	Nicol & Roaf [8]	26.7~29.9
UK	Rijal & Stevenson [9]	22.9

T_c: Comfort temp., *: Summer and autumn

COMFORT TEMPERATURE AND HUMIDITY

The comfort temperature is analyzed by relating with the relative humidity, absolute humidity and skin moisture. The comfort temperatures were correlated with the indoor relative humidity and skin moisture (Table 7). However, the correlation effect of the comfort temperature and relative humidity might have simply arrived from the correlation between air temperature and relative humidity. To investigate the effect of humidity on the comfort temperature, the multiple regression analysis was conducted for the NV mode.

T_{ci}=0.535T_i-0.032RH_i+14.1 (n=1860, R^2=0.32, p<0.001) (6)
T_{ci}=0.650T_i-0.128AH_i+10.8 (n=1860, R^2=0.32, p<0.001) (7)
T_{ci}=0.777T_i-1.307SM+7.2 (n=1860, R^2=0.56, p<0.001) (8)

T_{ci}: Comfort indoor temp. (°C), RH_i: Indoor relative humidity (%), AH_i: Indoor absolute humidity (g/kg'), SM: Skin moisture.

As shown in the equations, the relative humidity and absolute humidity have no important effect on the comfort temperature. As for the skin moisture, it has significantly effected to the comfort temperature (Fig. 6). The results showed that the evaporation of the skin moisture is important to increase the summer comfort temperature.

Table 7: Correlation coefficient in NV mode

Items	T_{ci}:RH_i	T_{cg}:RH_i	T_{ci}:AH_i	T_{cg}:AH_i	T_{ci}:SM	T_{cg}:SM
r	-0.37	-0.34	-0.03	-0.01	-0.35	-0.34
p	<0.001	<0.001	0.135	0.784	<0.001	<0.001
N	1,860	1,860	1,860	1,860	1,860	1,915

r: Correlation coefficient, p: Significant level, N: Number of sample, T_{ci}: Comfort indoor temp. (°C), T_{cq}, Comfort globe temp. (°C), RH_i: Indoor relative humidity (%), AH_i: Indoor absolute humidity (g/kg'), SM: Skin moisture.

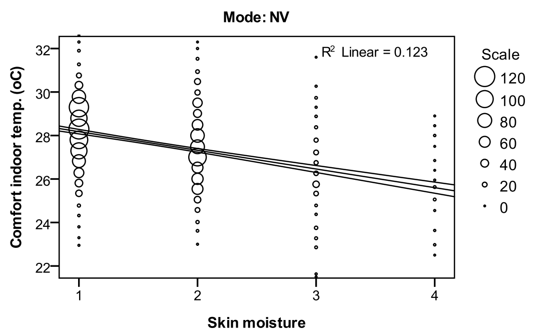

Figure 6: Relation between the comfort air temperature and the skin moisture (1. None, 2. Slightly, 3. Moderate, 4. Profuse).

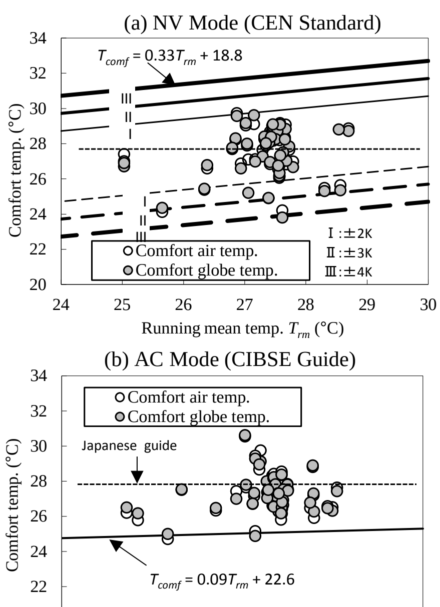

Figure 7: Comparison with the adaptive model.

A COMPARISION WITH THE ADAPTIVE MODEL

Fig. 7 shows the relation between the comfort temperature and the running mean outdoor temperature. The six lines in the figure show acceptable zone of the adaptive model [15]. Generally comfort temperature of this study is within the acceptable zone of the CEN standard. As for the AC mode, the comfort temperature is higher than the CIBSE guide [16]. The results showed that the residents are living by adapting to higher indoor air temperature of the houses.

OCCUPANT BEHAVIOUR

Residents can regulate the thermal environments by using various adaptations: behavioural, physiological and psychological. This section focuses on the behavioural adaptation. Nicol and Humphreys [17] made use of logistic regression analysis to predict occupant control behaviour in naturally ventilated buildings. We have also adopted the logistic regression method here, using SPSS version 19 for the calculations. The following regression equations were obtained for NV mode.

Window opening

$$\text{logit}(p)=0.239T_i-5.3 \quad (n=1860,\ R^2=0.02,\ p<0.001) \quad (9)$$

$$\text{logit}(p)=0.250T_g-5.6 \quad (n=1915,\ R^2=0.02,\ p<0.001) \quad (10)$$

$$\text{logit}(p)=0.109T_o-1.4 \quad (n=1915,\ R^2=0.01,\ p<0.001) \quad (11)$$

Fan use

$$\text{logit}(p)=0.309T_i-9.1 \quad (n=1860,\ R^2=0.05,\ p<0.001) \quad (12)$$

$$\text{logit}(p)=0.289T_g-8.6 \quad (n=1915,\ R^2=0.05,\ p<0.001) \quad (13)$$

$$\text{logit}(p)=0.206T_o-5.9 \quad (n=1915,\ R^2=0.05,\ p<0.001) \quad (14)$$

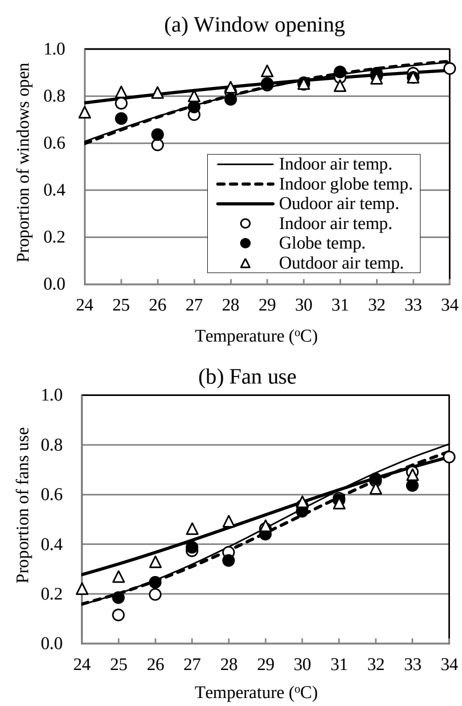

Figure 8: Proportion of window opening and fan use.

Where T_i is indoor air temperature (°C), T_g is indoor globe temperature (°C), T_o is outdoor air temperature (°C) and R^2 is Cox and Snell R^2. The regression coefficient for indoor air temperature or globe temperature is higher than the outdoor air temperature. It seems that the occupants respond more closely to the indoor temperature than outdoor air temperature while operating the windows and fans.

Fig. 8 shows the relationship between the windows open or fan use and temperature. The predicted window opening or fan use is well matched with the measured values. The proportion of window opening or fan use is increased when temperature rises. Thus, the results showed that residents undertake behavioural adaptation to regulate their summer thermal environment.

CONCLUSIONS

In order to clarify the comfort temperature and to investigate the adaptive model in Japanese houses, we conducted a thermal comfort survey in 30 living rooms for summer in Kanto region of Japan. Following are the results:

1. The residents are highly satisfied with the thermal environment of their houses.
2. The comfort temperature in NV mode is 27.6±1.8 °C in summer. The results showed that people are highly adapted in the thermal condition of the houses, and thus the thermal comfort zone is wider than the conventional standard.
3. The comfort temperature of this study is within the acceptable zone of the CEN standard.
4. The residents adapt to the hot environments using through the behavioural adaptive actions such as opening the windows and using fans.

ACKNOWLEDGEMENTS

This research was supported by Grant-in-Aid for Scientific Research (C) Number 24560726. I would like to thank to Dr. Madhavi Indraganti for editing the paper. I would like to give especial thanks to Prof. Michael Humphreys and Prof. Fergus Nicol of Oxford Brookes University for their research guidance.

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