Proceedings of 7th Windsor Conference: ***The changing context of comfort in an unpredictable world*** Cumberland Lodge, Windsor, UK, 12-15 April 2012. London: Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Investigation of window opening behaviour in Japanese houses

Hom B Rijal[1] and Takashi Nakaya[2]

[1]Dept. of Environmental and Information Studies, Tokyo City University, Japan
[2]Dept. of Architecture, Gifu National College of Technology, Japan

Abstract
We have investigated the window opening behaviour and thermal environment in Japanese houses for one year. The proportion of '*open window*' in the naturally ventilated mode is significantly higher than that of the air conditioned mode. The window opening is related to the indoor or outdoor air temperature. The window opening behaviour predicted by the logistic regression analysis is in agreement with the measured data. The deadband was narrower and constraints on the window opening in the investigated houses were considerably lower than previously found in office buildings. These findings can be applied to develop an adaptive algorithm for window opening behaviour in residences leading to optimal energy use.

Keywords
Window; House; Air temperature; Logistic regression; Deadband; Constraints

1. Introduction

In recent years, increased use of mechanical ventilation and air conditioning systems resulted in reduced natural ventilation which is achieved by opening of windows in residences. The improvement of the thermal environment is one of the important issues in hot and humid climates. The opening of windows would not only be effective in reducing the environmental impact and also in eliminating the air conditioner usage. Therefore, it is important to introduce natural ventilation through open windows, and to minimize the period of the air conditioning usage as much as possible in hot summer and other moderate seasons.

The window opening behaviour in the University campus (Suzuki et al. 2002, Umemiya & Yoshida 2004) and in the office building (Rijal et al. 2007, Yun & Steemers 2007, Haldi & Robinson 2010, Robinson & Haldi 2008, Kim et al. 2009) is well researched. However, there are only a few studies in residential buildings (Dick & Thomas 1951, Asawa et al. 2005, Kubo 2007), and thus the resulting environmental adjustment by the window opening is not clear. The aforementioned surveys were exclusively in non-domestic buildings. There is evidence that people respond differently in their own homes for a number of reasons: social, economic and cultural (Oseland, 1995). The window opening algorithm (Rijal et al. 2012) developed for work environments may not reflect domestic occupant behaviour adequately.

The residents actively open the window to adjust the indoor thermal environment, as there are fewer constraints on the window opening at home than one might encounter in an office building. The indoor thermal environment is often adjusted using the air conditioning in the office building to improve the thermal comfort and productivity. On the contrary, the same is achieved at home through window operation, as the use of air conditioning has a direct financial implication on the household. Thus, it is necessary to conduct research on residential window opening behaviour as well.

Addressing this need, we investigated the window opening behaviour and corresponding thermal environment in living rooms for one year in Gifu region of Japan, and analyzed the relation between the window opening behaviour and air temperature. We also quantified the deadband and constraints on window opening in terms of indoor or outdoor air temperature.

2. Methodology

A thermal comfort survey and the thermal measurement were conducted in 30 houses in Gifu region of Japan during 13 May 2010 to 31 May 2011. The indoor air temperature and relative humidity were measured in the living room at ten minute intervals using a data logger (Fig. 1). The number of subjects is 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 a nine point thermal sensation scale (Fig. 2). The window opening behaviour in the living room was recorded in binary form several times in a day (0 = window closed, 1 = window open). We collected more than 21,000 samples of data. Outdoor air temperature and relative humidity were obtained from the nearest meteorological station.

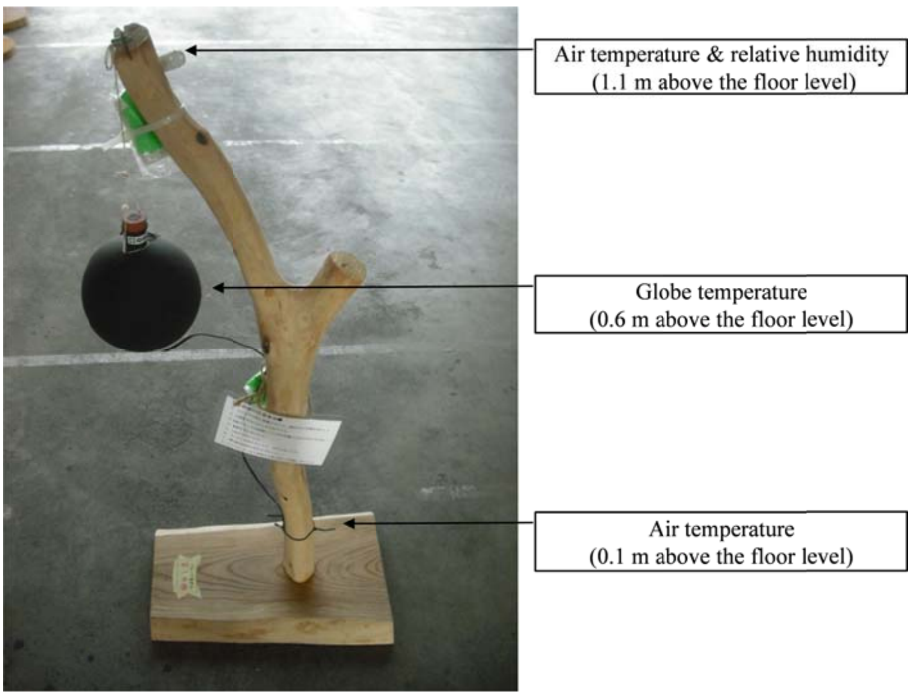


Fig. 1 Details of the thermal measurement

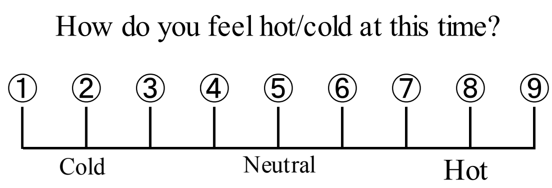


Fig. 2 Thermal sensation scale

3. Results and discussion

3.1 The thermal environment

In this section, the thermal environment during the voting is described. The data were divided in the NV mode (naturally ventilated), AC mode (cooling by air conditioning) and HT mode (heating).

Fig. 3 shows the distribution of indoor air temperature in each mode. The mean indoor air temperature is 22.7 °C in NV mode, 28.0 °C in AC mode and 17.7 °C in the HT mode. 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 temperature setting in AC mode is same as the recommendation. However, it is 2.3 K lower than the recommended value in the HT mode.

Fig. 4 shows the distribution of outdoor air temperature in each mode. The mean outdoor air temperature is 18.8 °C, 28.9 °C and 6.7 °C for NV, AC and HT modes respectively. In addition, the mean indoor and outdoor temperature difference is 3.9 K, -0.8 K and 11.0 K for NV, AC and HT modes respectively. The results establish that the data is collected over a wide range of indoor or outdoor air temperatures.

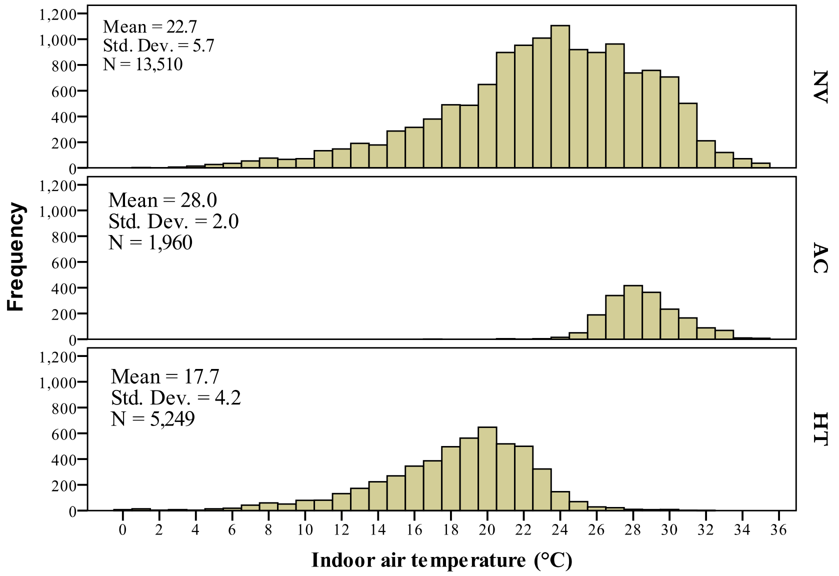


Fig. 3 Distribution of indoor air temperature in various modes.

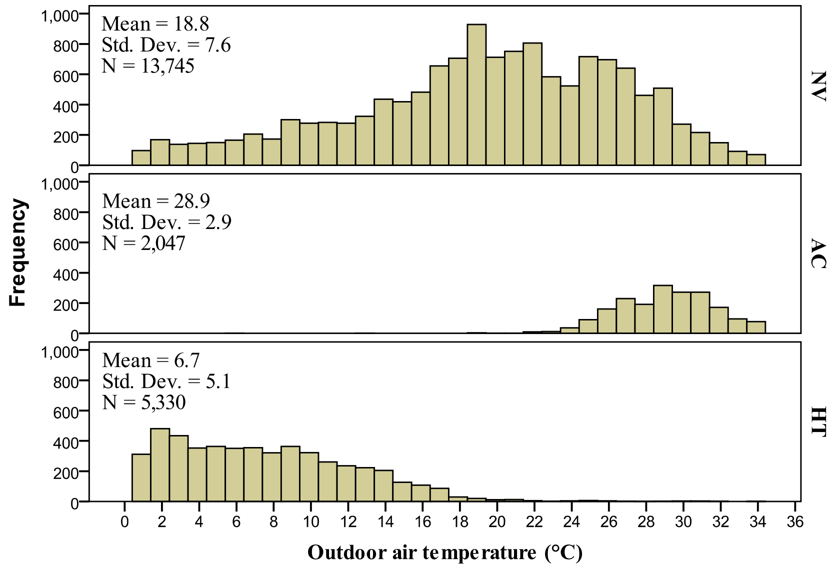


Fig. 4 Distribution of outdoor air temperature in various modes

3.2 Evaluation of window opening behaviour

3.2.1 Status of window opening (WO)

To understand the window opening behaviour further, the mean proportions of 'window opening (WO)' in all the houses are compared. Table 1 shows the indoor air temperature and proportion of open windows of all the houses.

The mean 'open window' for all data is 0.22. When we compared separately, the mean value ranged from 0.00 to 0.49, and is less than 0.10 for seven houses.

Table 2 shows the mean and standard deviation of the windows open in each mode. The mean WO is 0.32, 0.08 and 0.02 for NV, AC and HT modes respectively (Table 2). Interestingly, the mean WO in UK office buildings was 0.70 in NV mode and 0.04 in AC mode (Rijal et al. 2007). The mean windows open in Pakistan office and commercial buildings was 0.33 in NV mode. The results showed that the mean windows open is close to the Pakistan and lower than the UK. As the WO is considerably low in the AC and HT modes, we shall limit the analysis to the NV mode in this research.

Table 1 Indoor air temperature and proportion of open windows in all the houses

Group	House	Indoor air temp. T_i (°C)			Windows open		
		N	Mean	SD	N	Mean	SD
A	1	1,367	23.8	4.7	1,373	0.19	0.39
	2	738	22.6	4.4	745	0.05	0.22
	3	688	21.1	5.8	689	0.04	0.20
	4	821	21.7	4.8	824	0.05	0.22
	5	202	25.1	3.1	208	0.15	0.36
	6	803	20.4	6.1	825	0.24	0.43
	7	799	22.1	6.4	800	0.10	0.31
	8	583	23.9	4.4	585	0.03	0.18
	9	340	24.2	4.9	338	0.39	0.49
	10	600	22.4	4.5	664	0.23	0.42
B	1	725	21.7	5.7	733	0.23	0.42
	2	718	20.7	6.9	723	0.18	0.38
	3	735	17.5	8.3	735	0.39	0.49
	4	540	22.9	5.2	543	0.35	0.48
	5	455	21.6	5.9	478	0.31	0.46
	6	1,533	20.7	5.6	1,535	0.21	0.41
	7	331	20.6	6.6	348	0.00	0.00
	8	758	23.1	4.4	758	0.22	0.41
	9	225	22.8	4.8	223	0.04	0.19
	10	192	25.4	3.9	256	0.37	0.48
C	1	767	20.4	6.3	767	0.02	0.13
	2	346	20.1	7.7	377	0.23	0.42
	3	807	22.6	4.8	728	0.37	0.48
	4	727	22.9	5.3	738	0.26	0.44
	5	134	25.7	4.6	140	0.28	0.45
	6	1,320	21.4	5.8	1,326	0.33	0.47
	7	844	20.7	7.9	872	0.14	0.34
	8	641	24.6	5.3	639	0.49	0.50
	9	1,129	22.5	4.7	1,130	0.26	0.44
	10	851	21.6	3.7	1,188	0.33	0.47
All		20,719	21.9	5.8	21,288	0.22	0.41

N: Number of observation, SD: Standard deviation

Table 2 Indoor air temperature and proportion of open windows in various modes

Mode	Open windows		
	Number of observations	Mean	Standard deviation
NV	13,843	0.32	0.47
AC	2,108	0.08	0.27
HT	5,337	0.02	0.14

3.2.2. Season, month and time of the day

Seasonal difference in proportion of windows open in NV mode is shown in Fig. 5. The proportion of open windows (WO) is highest in summer and lowest in winter. The WO in autumn is significantly higher than that in spring. This is possibly due to the fact that people are more adapted in spring to the winter low temperature, and in autumn to the summer temperature. In reality, the indoor and outdoor air temperatures in autumn are higher than that of spring (Fig. 6).

Evidently, the proportion of open windows gradually increases towards the summer months. Conversely, it gently decreases towards the winter months as indoor or outdoor air temperature varies (Figs. 7 & 8).

The data were divided into four groups, in ascending order of time. Interestingly, the proportion of open windows gradually increases early morning to morning, and then decreases towards the evening (Fig. 9). Most of occupants open the windows in morning, and shut them at night. These trends are similar for all seasons (Fig. 10).

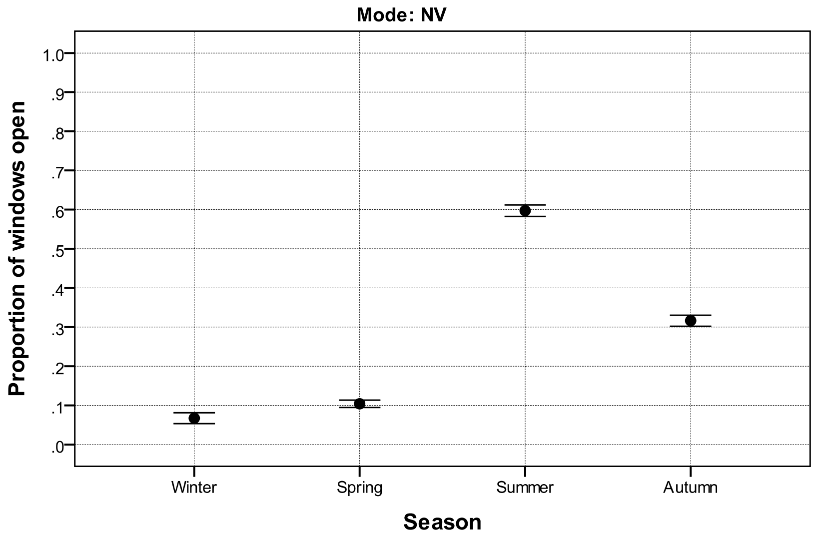


Fig. 5 Seasonal differences in the proportion of open windows (at 95% confidence level)

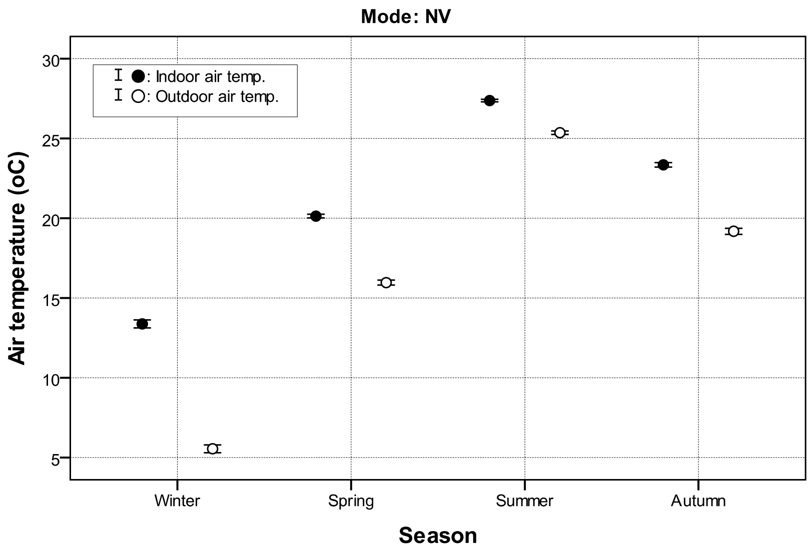


Fig. 6 Seasonal differences in indoor and outdoor air temperature (at 95% confidence level)

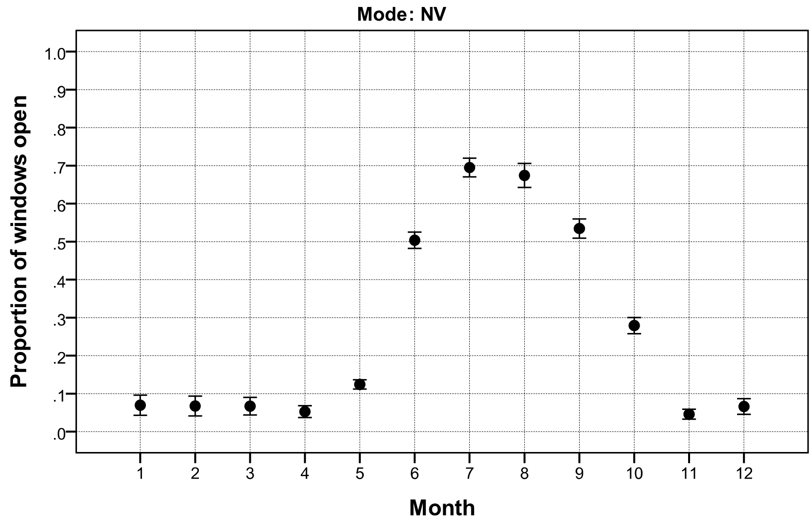


Fig. 7 The proportion of open windows each month (at 95% confidence level)

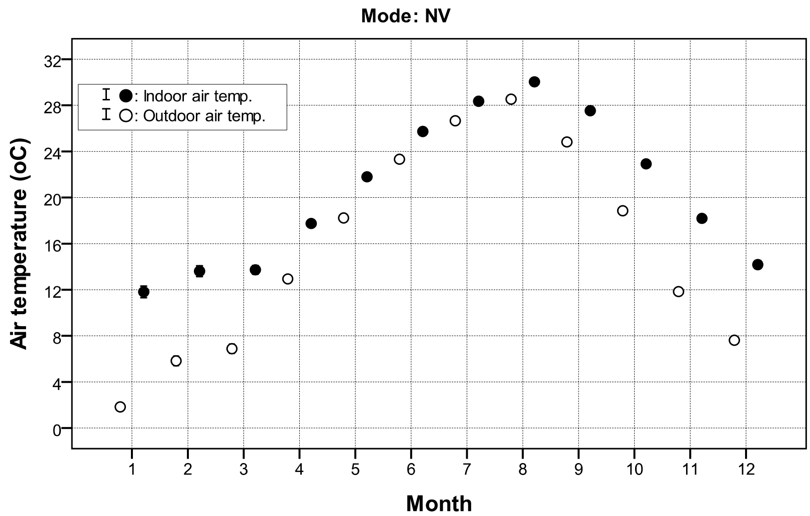


Fig. 8 Monthly mean indoor and outdoor air temperature (at 95% confidence level)

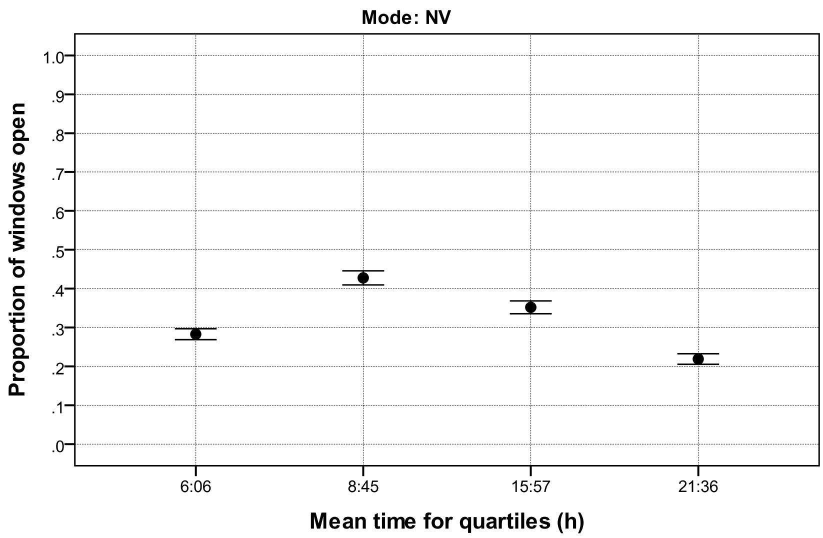


Fig. 9 Proportion of open windows at 95% confidence intervals of time-of-day

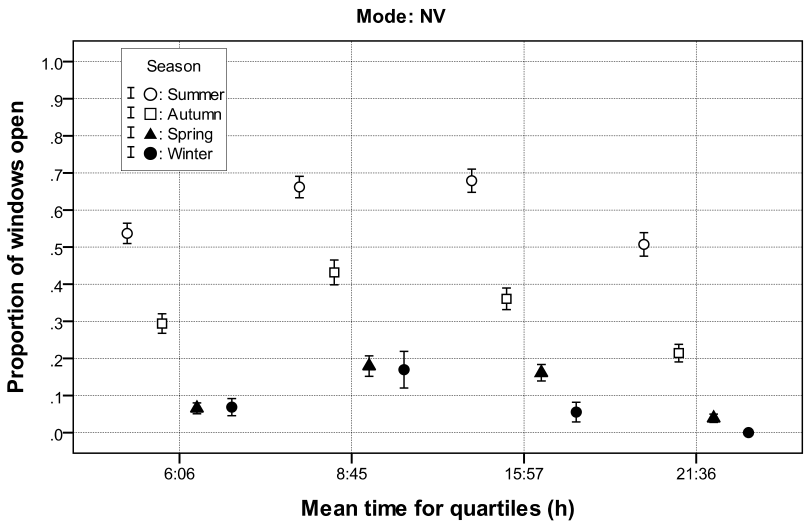


Fig. 10 Seasonal differences in the proportion of open windows (at 95% confidence intervals of time-of-day)

3.2.3 Relationship between the open windows and air temperature

In NV mode the open window correlated better with the indoor temperature (r= 0.43) than with the outdoor temperature (Table 3), similar to that of the Pakistan study where globe temperature correlated with open window at 0.43 (Rijal et al. 2008). Interestingly, in Pakistan study, they found a slightly weaker relationship between open window and outdoor temperature (r = 0.41) than the correlation obtained in this study. From these observations, it can be inferred that the window opening is related to both indoor and outdoor air temperatures.

Table 4 and Fig. 11 show the proportion of the open window and the corresponding indoor and outdoor air temperatures. The data were divided randomly into ten groups, in an ascending order of temperature. The proportion of the window opening rises as the indoor or outdoor air temperature rises. When mean indoor air temperature is 26.7 °C, the proportion of open windows is 0.47 (Fig. 11(a)).

On the other hand, when the mean outdoor air temperature is 24.6 °C, the proportion of the windows open is 0.54 (Fig. 11(b)). These proportions are similar to the Pakistan study (Rijal et al. 2008), and significantly lower than that of the UK study (Rijal et al. 2007). It can be reasoned that the indoor and outdoor air temperature in Japan and Pakistan are significantly higher than that of UK.

Table 3 Correlation coefficients in NV mode

Items	Window: T_i	Window: T_o	T_i: T_o
Correlation coefficient	0.43	0.48	0.91
Number of samples	13,413	13,647	13,510
Significant level	p<0.001	p<0.001	p<0.001

T_i: Indoor air temperature (°C), T_o: Outdoor air temperature (°C)

Table 4 Deciles of indoor air temperature, outdoor air temperature and the proportion of open windows

Deciles	Indoor air temp. (T_i) & windows open						Outdoor air temp. (T_o) & windows open					
	T_i (°C)			Windows open			T_o (°C)			Windows open		
	N	Mean	SD	N	Mean	SD	N	Mean	SD	N	Mean	SD
1	1,345	11.4	3.0	1,339	0.09	0.29	1,376	3.8	2.7	1,352	0.06	0.24
2	1,340	16.9	0.9	1,331	0.08	0.27	1,367	10.3	1.4	1,345	0.04	0.20
3	1,378	19.6	0.6	1,348	0.09	0.28	1,366	14.4	0.9	1,353	0.08	0.27
4	1,305	21.2	0.4	1,291	0.11	0.31	1,358	16.9	0.6	1,346	0.15	0.36
5	1,420	22.6	0.4	1,412	0.18	0.39	1,379	18.6	0.4	1,374	0.17	0.38
6	1,293	23.8	0.4	1,281	0.29	0.45	1,414	20.5	0.6	1,410	0.27	0.44
7	1,392	25.3	0.4	1,385	0.37	0.48	1,347	22.4	0.6	1,342	0.39	0.49
8	1,303	26.7	0.4	1,296	0.47	0.50	1,384	24.6	0.6	1,377	0.54	0.50
9	1,411	28.5	0.5	1,411	0.65	0.48	1,362	26.7	0.7	1,359	0.63	0.48
10	1,323	30.9	1.3	1,319	0.76	0.43	1,392	30.2	2.0	1,389	0.78	0.42

N: Number of observation, SD: Standard deviation

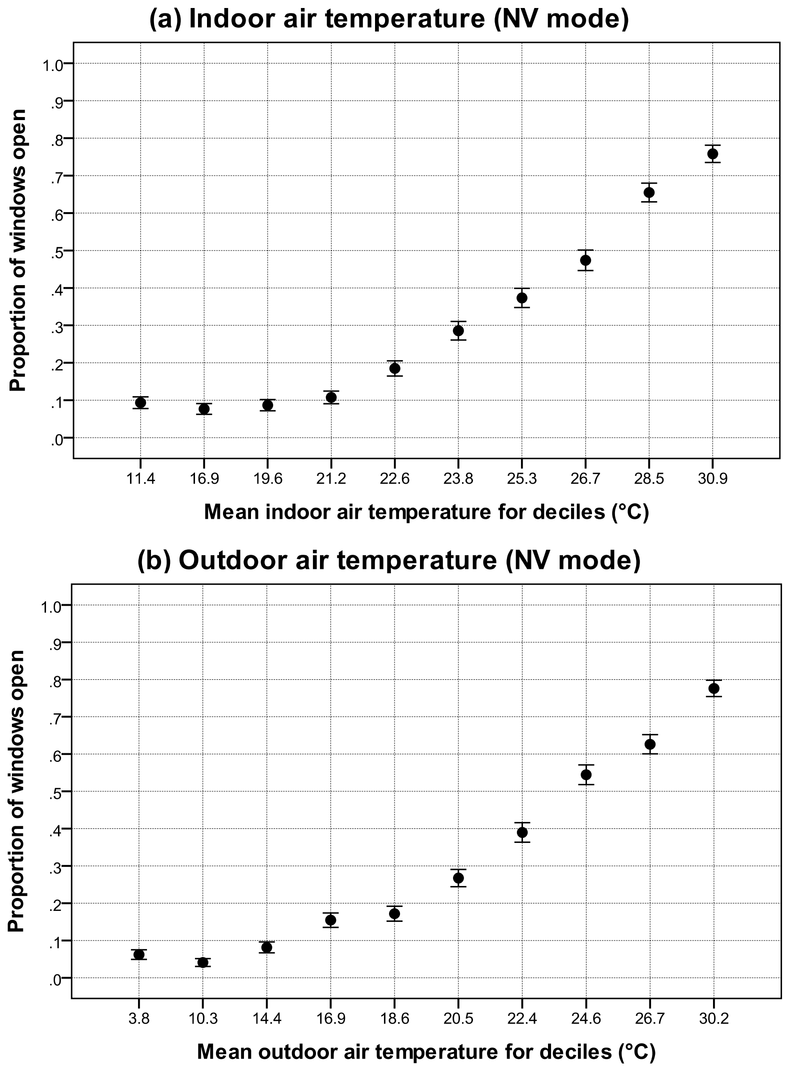


Fig. 11 Proportion of open windows at 95% confidence intervals at deciles of indoor or outdoor air temperature

3.3 Potential of the open window

3.3.1 Indoor air temperature

Fig. 12 and Table 5 show the seasonal variation in indoor air temperature for cases when windows are open and closed. The mean indoor air temperature for window open is 26.3 °C which is significantly higher by 5.2 K, than the window closed. In UK office buildings, the mean globe temperature for window open is 23.4 °C which is 1.2 K higher than when the window is closed (Rijal et al. 2008a). Thus, the temperature difference between the cases of open and closed window in residential buildings is higher than that of the office buildings. The temperature difference is highest in autumn and lowest in spring. In winter, the mean indoor air temperature for 'open window' case is significantly lower than that of the 'closed window'. The results showed that window opening is effective to control the indoor environment.

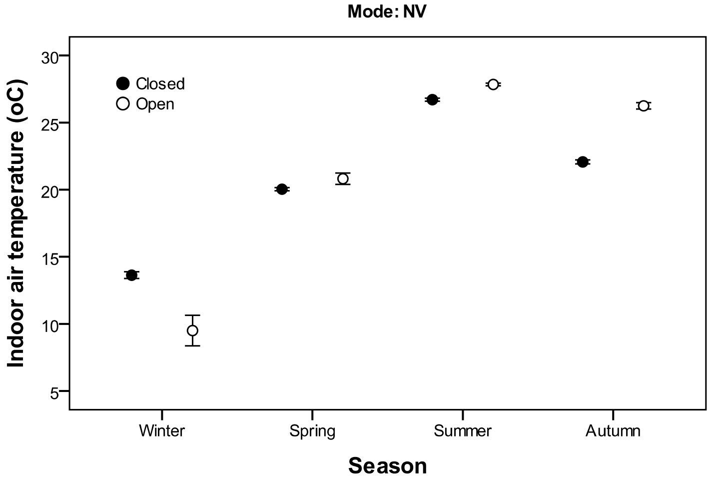


Fig. 12 Seasonal variation of indoor air temperature for windows open and closed

Table 5 Indoor air temperature and comfort temperature for windows open and closed

Season	Window	Indoor air temperature T_i (°C)					Open - Closed (K)
		N	Mean	SD	t	p	
Winter	Closed	1,151	13.6	4.3	8.5	<0.001	-4.1
	Open	86	9.5	5.3			
Spring	Closed	3,604	20.0	3.7	-4.0	0.001	0.8
	Open	416	20.8	4.4			
Summer	Closed	1,682	26.7	2.4	-14.2	<0.001	1.1
	Open	2,433	27.8	2.6			
Autumn	Closed	2,811	22.1	3.9	-30.4	<0.001	4.2
	Open	1,230	26.2	4.2			
All	Closed	9,248	21.1	5.2	-55.7	<0.001	5.2
	Open	4,165	26.3	4.7			

3.3.2 Comfort temperature

The potential of the open window is further analyzed in the context of comfort temperature. At first, the comfort temperature was predicted by 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, where 0.25, 0.33 and 0.50 are the regression coefficients 1) often obtained in the field survey; 2) from the laboratory experiment of Fanger by the Probit method; and 3) often used (Rijal et al. 2008, Humphreys et al. 2010) respectively.

We have investigated the comfort temperature using these three regression coefficients. These were converted to represent the nine point sensation scale (see Fig. 2). It resulted in the following: 1) 0.33 (=0.25×8/6), 2) 0.44 (=0.33×8/6) and 3) 0.67 (=0.50×8/6). The mean comfort temperatures obtained with the three regression coefficients are very similar (Honjou et al. 2012), and thus the comfort temperature which is predicted by 0.67 is used in this analysis.

Fig. 13 and Table 6 show the seasonal variation in comfort temperature with windows open and closed. The mean comfort temperature for window open is 25.4 °C which is 3.8 K higher than that of the case of window closed. Brager et al. (2004) found 1.5 K higher comfort temperature for the people with an access to window operation than the group without in office buildings.

Moreover, the window opening in houses is likely to be more effective than in the office building. The temperature difference in outdoor and indoor temperature is highest in autumn and lowest in spring and summer. In winter, the mean comfort temperature for open window is significantly lower than the window closed. The results showed that window opening is effective to create the comfortable thermal environment.

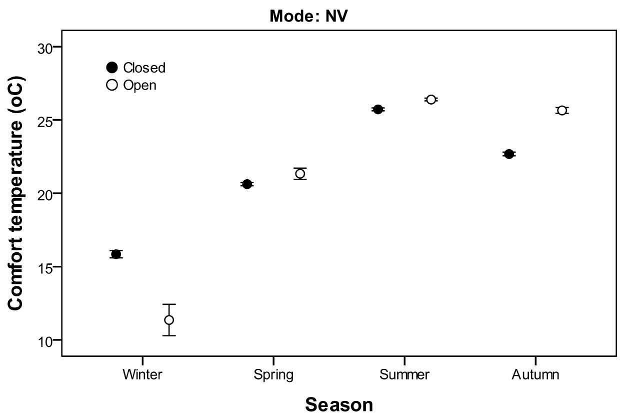


Fig. 13 Seasonal variation in comfort temperature for windows open and closed

Table 6 Comfort temperature for windows open and closed

Season	Window	Comfort temperature T_c (°C)					Open - Closed (K)
		N	Mean	SD	t	p	
Winter	Closed	1,148	15.8	4.2	9.4	<0.001	-4.5
	Open	86	11.4	5.0			
Spring	Closed	3,599	20.6	3.3	-4.0	0.001	0.7
	Open	416	21.3	4.0			
Summer	Closed	1,681	25.7	2.1	-9.8	<0.001	0.7
	Open	2,431	26.4	2.3			
Autumn	Closed	2,804	22.7	3.3	-25.6	<0.001	3.0
	Open	1,226	25.7	3.5			
All	Closed	9,232	21.6	4.3	-48.4	<0.001	3.8
	Open	4,159	25.4	3.9			

3.4 Development of an algorithm to predict window opening behaviour

3.4.1 Logistic regression curves

In the previous section, we analyzed the window opening behaviour based on field data and confirmed some general behavioural trends, but no attempt was made to predict the occupant behaviour in housing. Such predictions are needed for the thermal simulation of buildings.

Nicol and Humphreys (2004) made use of Probit analysis to predict occupant control behaviour in NV buildings. For mathematical convenience they used a Logistic distribution in place of the Normal distribution. The relationship between the probability of windows open (p) and the indoor or outdoor temperature (T) is of the form:

$$\mathrm{logit(p)} = \log \{p/(1-p)\} = \mathrm{b}T + \mathrm{c} \quad (2)$$

where

$$p = \exp^{(\mathrm{b}T+\mathrm{c})}/\{1+\exp^{(\mathrm{b}T+\mathrm{c})}\} \quad (3)$$

and where exp (exponential function) is the base of natural logarithm, b is the regression coefficient for T, and c the constant in the regression equation.

We have adopted the same method here, using SPSS version 19 for the calculations. The Logistic regression equations, based on the indoor or outdoor temperature, are shown in Figs. 14 and 15 and Table 7. The following regression equations were obtained for all data in between the windows open and the indoor or outdoor air temperature:

$$\mathrm{logit(p)}=0.248T_i - 6.733 \quad (n=13{,}413,\ R^2=0.21,\ p<0.001) \quad (4)$$

$$\mathrm{logit(p)}=0.210T_o - 5.147 \quad (n=13{,}647,\ R^2=0.25,\ p<0.001) \quad (5)$$

T_i: Indoor air temperature (°C), T_o: Outdoor air temperature (°C), n: Number of sample, p: Significance level of the regression coefficient, R^2: Cox and Snell R^2

In this study a regression coefficient of 0.248 is obtained when the open window and indoor air temperature are regressed. This is slightly higher than that obtained when open window is regressed with the outdoor air temperature. However, in Pakistan (Rijal et al. 2007) and in UK (Rijal et al. 2007) studies, regression coefficients of 0.176 and 0.354 respectively were obtained when open window is regressed with globe temperature. On the contrary, Kyoto (Majima et al. 2007) and UK (Rijal et al. 2007) studies returned the regression coefficients of 0.119 and 0.181 respectively when open window is regressed with outdoor air temperature. The results reconfirm our premise that the occupants respond better to the indoor temperature than outdoor air temperature while operating the windows.

The predicted window opening is well matched with measured values (Fig. 14).The prediction of window opening is quite different in each house (Fig. 15). Perhaps, the window opening is not only related to the temperatures, and but also to other factors such as ventilation requirements, habits etc. In this study, we only investigated the physical factors for the window opening, and thus the psychological factors need to be investigated in future.

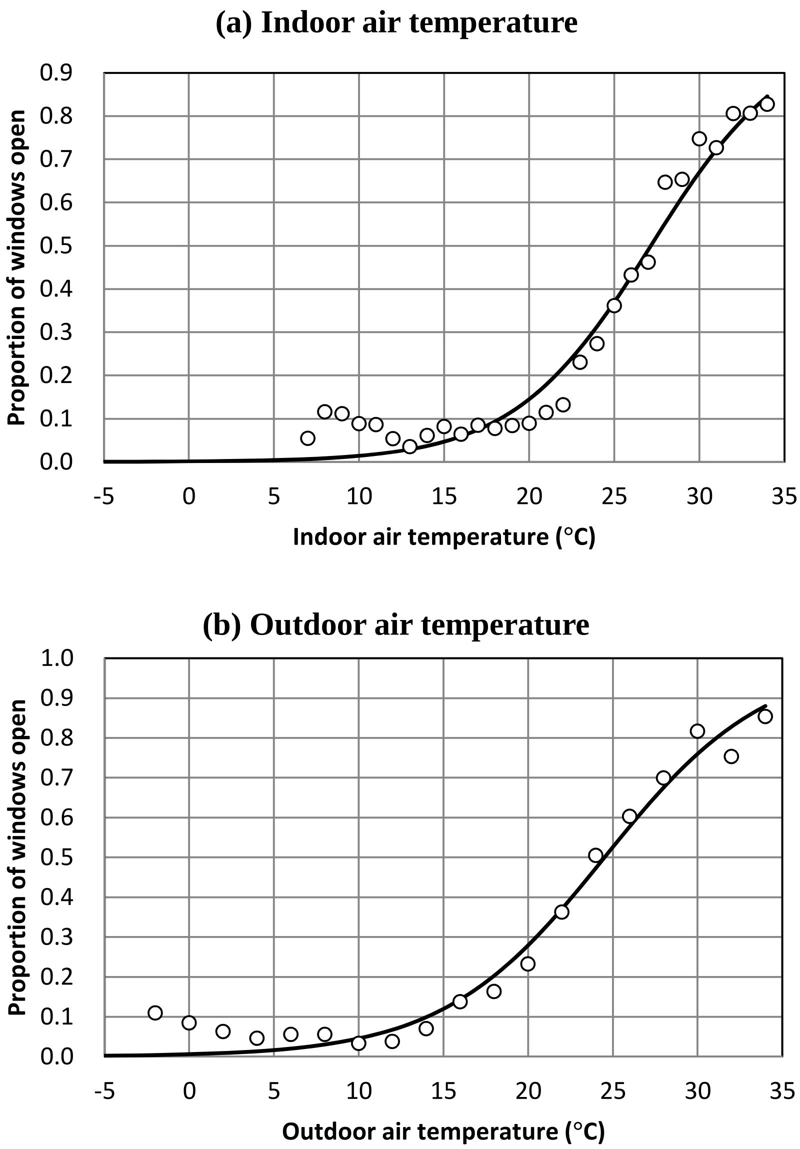


Fig. 14 Comparison of measured (open circular dots) and predicted value (curved line) in NV mode. Measured values were grouped for every 1 °C for indoor air temperature and for every 2 °C for outdoor air temperature. The grouped data for samples less than 50 are not shown. The proportion of windows open was predicted by using the equations shown in Table 7.

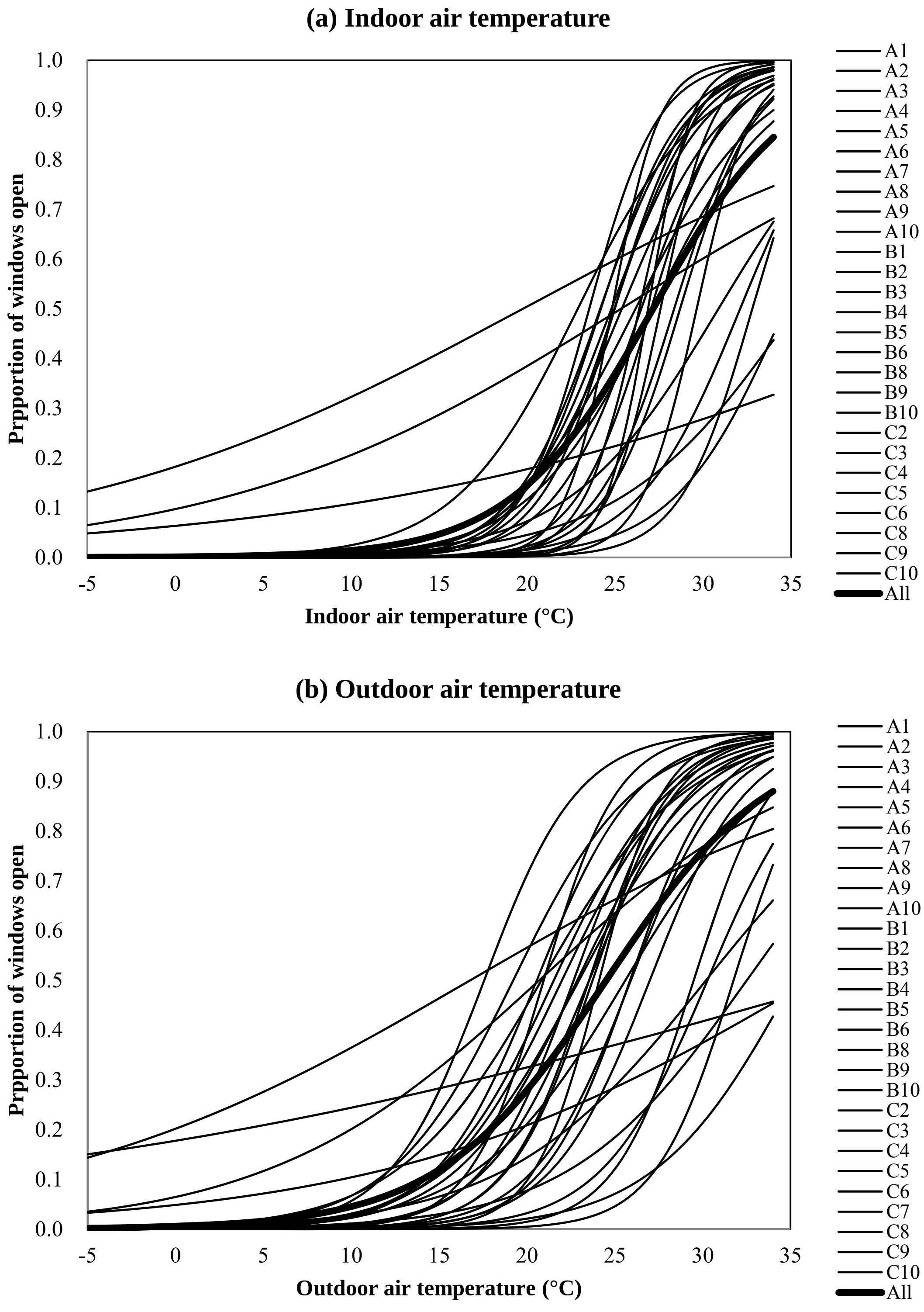


Fig. 15 Relationship between the open windows and outdoor air temperature in every house and in all the houses in NV mode. The proportion of windows open was predicted by using the equations of Table 7.

Table 7 Prediction of the window opening behaviour by logistic regression analysis

House	Indoor air temperature T_i (°C)				Outdoor air temperature T_o (°C)			
	Equation	N	R^2	p	Equation	N	R^2	p
A1	logit=0.451T_i-12.788	1,088	0.32	<0.001	logit=0.402T_o-10.398	1,088	0.40	<0.001
A2	logit=0.200T_i-7.052	347	0.05	<0.001	logit=0.198T_o-6.437	347	0.09	<0.001
A3	logit=0.634T_i-18.788	383	0.17	<0.001	logit=0.442T_o-13.035	383	0.21	<0.001
A4	logit=0.344T_i-11.043	359	0.14	<0.001	logit=0.331T_o-10.02	359	0.18	<0.001
A5	logit=0.668T_i-18.421	132	0.22	<0.001	logit=0.543T_o-13.088	132	0.34	<0.001
A6	logit=0.434T_i-10.497	470	0.35	<0.001	logit=0.385T_o-8.723	470	0.37	<0.001
A7	logit=0.058Ti-2.693	435	0.02	0.015	logit=0.082T_o-2.972	435	0.04	<0.001
A8	logit=0.486T_i-15.939	324	0.07	<0.001	logit=0.449T_o-14.259	324	0.13	<0.001
A9	logit=0.749T_i-18.592	259	0.46	<0.001	logit=0.473T_o-9.911	259	0.45	<0.001
A10	logit=0.400T_i-10.592	438	0.27	<0.001	logit=0.265T_o-6.085	491	0.32	<0.001
B1	logit=0.285T_i-7.723	538	0.32	<0.001	logit=0.235T_o-6.016	538	0.34	<0.001
B2	logit=0.466T_i-13.371	570	0.40	<0.001	logit=0.358T_o-9.662	570	0.39	<0.001
B3	logit=0.076T_i-1.501	608	0.09	<0.001	logit=0.082T_o-1.375	608	0.12	<0.001
B4	logit=0.286T_i-6.542	358	0.29	<0.001	logit=0.286T_o-5.495	358	0.40	<0.001
B5	logit=0.426T_i-10.63	385	0.46	<0.001	logit=0.338T_o-7.956	393	0.46	<0.001
B6	logit=0.374T_i-9.27	840	0.32	<0.001	logit=0.295T_o-6.488	840	0.34	<0.001
B8	logit=0.634T_i-16.719	453	0.46	<0.001	logit=0.413T_o-9.803	453	0.47	<0.001
B9	logit=0.316T_i-10.949	135	0.03	0.050	logit=0.253T_o-8.895	135	0.04	0.035
B10	logit=0.47T_i-12.709	177	0.31	<0.001	logit=0.362T_o-9.381	216	0.33	<0.001
C2	logit=0.825T_i-22.167	337	0.54	<0.001	logit=0.423T_o-9.957	369	0.44	<0.001
C3	logit=0.513T_i-12.069	521	0.46	<0.001	logit=0.372T_o-6.535	521	0.49	<0.001
C4	logit=0.280T_i-7.324	471	0.27	<0.001	logit=0.243T_o-5.061	471	0.33	<0.001
C5	logit=0.234T_i-7.224	132	0.11	0.001	logit=0.175T_o-5.283	133	0.09	0.002
C6	logit=0.400T_i-9.661	1,014	0.39	<0.001	logit=0.302T_o-6.502	1,014	0.40	<0.001
C7	-	-	-	-	logit=0.04T_o-1.531	356	0.01	0.045
C8	logit=0.467T_i-11.666	534	0.42	<0.001	logit=0.347T_o-7.133	534	0.47	<0.001
C9	logit=0.341T_i-8.654	624	0.26	<0.001	logit=0.292T_o-6.675	624	0.30	<0.001
C10	logit=0.088T_i-2.229	366	0.01	0.025	logit=0.129T_o-2.67	431	0.11	<0.001
All	logit=0.248T_i-6.733	13,413	0.21	<0.001	logit=0.210T_o-5.147	13,647	0.25	<0.001

N: Number of observation, R^2: Cox and Snell R-Square, p: p-value of the regression coefficient.

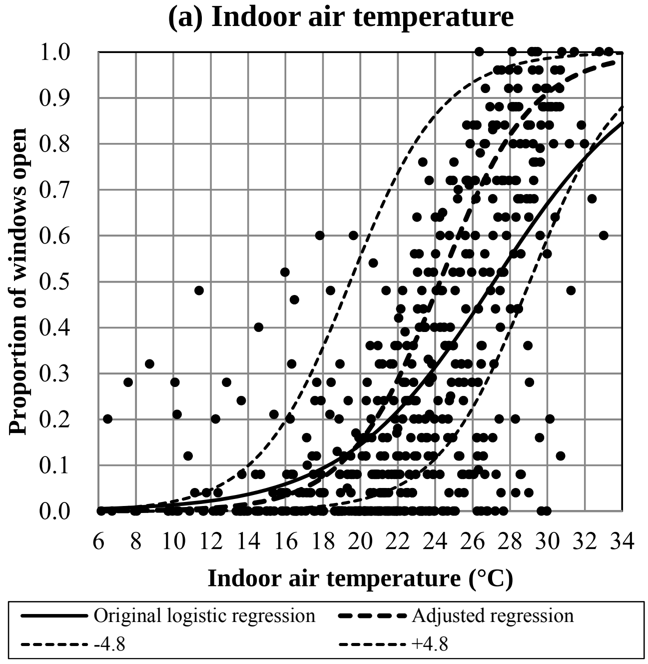
3.4.2 Deadband of temperature for window opening behaviour

(1) Indoor and outdoor air temperature

The proportion of windows open was plotted as a scatter diagram against the indoor or outdoor air temperature as shown in Fig. 16. In order to obtain the sets of points for plotting the data were sorted by building and indoor or outdoor temperature and then split into groups of 25 records each. However, the original regression line does not fit very well into the grouped data.

To determine the range of temperatures over which the windows remain change, the deadband of the window opening behaviour with respect to the indoor or outdoor air temperature is established. This is calculated for the grouped data, making due allowance for the error in the logit arising from the sample size of 25. The regression equation is further adjusted using the existing procedures (Rijal et al. 2008a). The procedures for adjustment are fully elaborated in Table 8.

As it can be seen in Fig. 16 (a), 82 % of the points are within ±4.8 K range of the regression line. The deadband is 4.8 K for indoor air temperature which is higher than that of UK (2.1 K) and lower than that of Pakistan (7.0 K) (Rijal et al. 2008; 2008a). (The deadband of the UK and Pakistan is based on globe temperature.) The deadband (5.4 K) with respect to the outdoor temperature interestingly compares well with that of UK (5.0 K) study (Rijal et al. 2007).



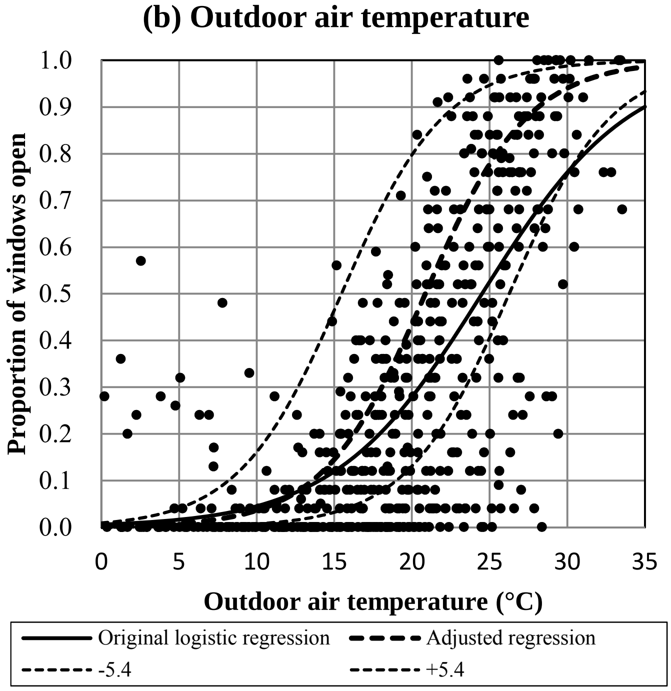


Fig. 16 Logistic regression curves of open window as a function of (a) indoor air temperature and (b) outdoor air temperature in all NV modes. Three lines (left, centre and right) are the deadband of windows open.

Table 8 Symbols and values of parameters used to calculate the adjusted regression equation for indoor and outdoor air temperature, based on the records grouped in 25s.

Parameter	Indoor air temp. (T_i)	Outdoor air temp. (T_o)
Air temperature: T	-	-
Logit of the windows open: logit	-	-
Regression coefficient of T on logit: b	2.128	2.863
Variance of logit: var(logit)	2.639	2.830
Covariance of T and logit: cov(T, logit)	5.516	8.102
Number of observations in each group: n	25	25
Proportion of windows open: p	0~1	0~1
Mean variance of logit error: var(logit error)	0.371	0.3874
Mean logit: $logit_m$	-0.6675	-0.6338
Mean air temperature: T_m	22.5	18.8
Residual of T	3.2	3.6
Notes: Steps in obtaining the adjusted equation		
Equation for regression coefficient	b=cov(T, logit)/var(logit)	
Therefore, the equation for covariance	cov (T, logit)=b×var(logit)	
Equation for logit error	var(logit error)= 1/{np(1−p)}	
Adjusted value of b	b=cov(T, logit)/{var(logit) −var(logit error)}	
The adjusted equation	T_i=2.476logit+c	T_o=3.316logit+c
Therefore, the equation for logit	logit=0.404T_i+c	logit=0.302T_o+c
The equation must pass through the T_m and the $logit_m$	c=$logit_m$−0.404T_m	c=$logit_m$−0.302T_m
The centre line of the deadband	logit=0.404T_i−9.8	logit=0.302T_o−6.3
The width of deadband	±1.5SD×Residual of T_i	±1.5SD×Residual of T_o
The equations for deadband margins	logit=0.404(T_i±4.8) −9.8	logit=0.302(T_o±5.4) −6.3
The proportion of windows open	$p=e^{(logit)}/\{1+e^{(logit)}\}$	

(2) Temperature departure from comfort temperature

The Logistic regression equation, based on the temperature departure from comfort temperature ($\Delta t=T_i-T_c$), is shown in Fig. 17. The following regression equations were obtained for all data in between the windows open and the temperature departure from comfort temperature:

$$logit(p)=0.536\Delta t-0.897 \quad (n=13,391, R^2=0.14, p<0.001)) \qquad (6)$$

Where, n: Number of sample, p: Significance level of the regression coefficient, R^2: Cox and Snell R^2. The predicted window opening is well matched with measured values. We corrected the equation using the existing procedure (Rijal et al. 2008).

We tried to establish the deadband of the window opening behaviour for the temperature departure from the comfort temperature. The grouped data (in groups of 25) with the original logistic regression is shown in Fig. 18. However, the original regression line does not fit very well with the grouped data.

The regression equation is adjusted using the existing procedures (Rijal et al. 2008). The adjusted procedures are fully described in Table 9. The deadband obtained in this study is 1.4 K which is smaller than that of UK (2.0K), Europe (2.3K) and Pakistan (2.8K) (Rijal et al. 2007; 2008) studies. (Please note that the deadband of the UK and Pakistan is based on globe temperature.) The difference could be attributed to the higher freedom available to the residents than office users in operating the windows.

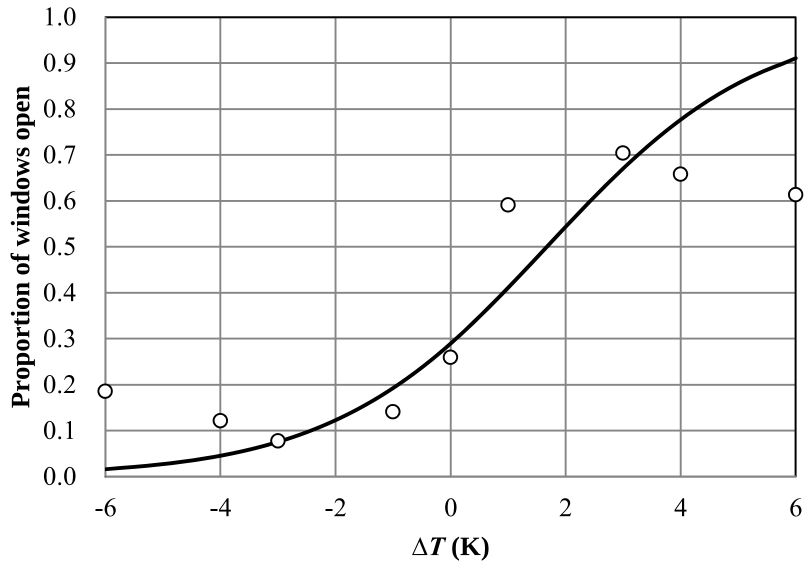


Fig. 17 Comparison between measured (open circles) and predicted (curved line) value. Measured values were grouped for every 1K. The proportion of windows open was predicted by using the equation (6).

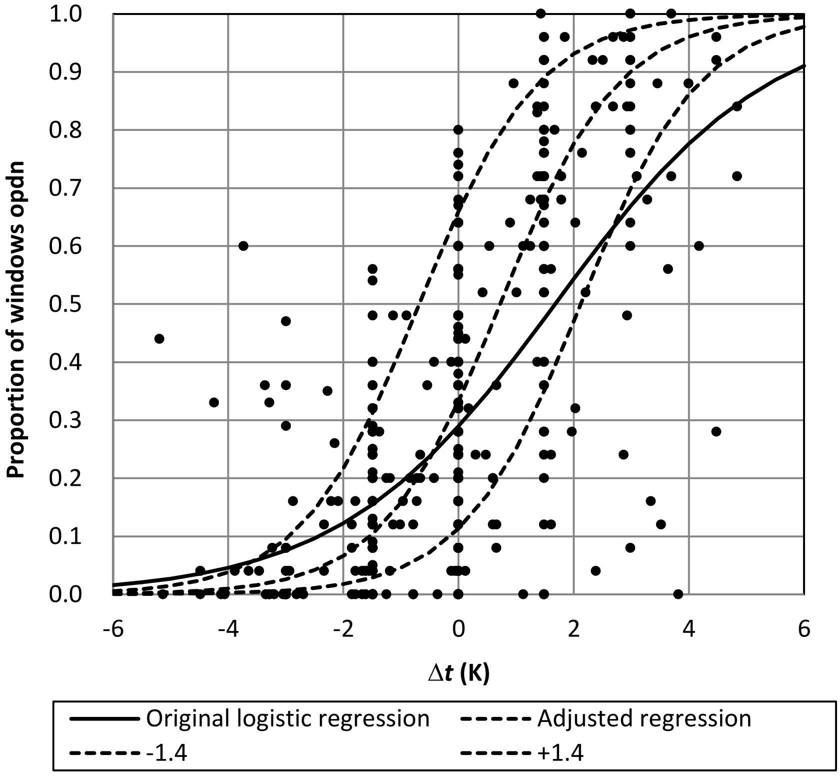


Fig. 18 Logistic regression curves of windows open as a function of Δt in all NV modes. Three lines (left, centre and right) represent the deadband of windows open.

Table 9 Symbols and values of parameters used to calculate the adjusted regression equation for the temperature departure from comfort temperature, based on the records grouped in 25s.

Parameter	Value
The temp. departure from comfort temp. ($\Delta t = T_i - T_c$)	-
Logit of the windows open: logit	-
Regression coefficient of Δt on logit: b	0.863
Variance of logit: var(logit)	2.321
Covariance of Δt and logit: cov(Δt, logit)	2.003
Number of observations in each group: n	25
Proportion of windows open: p	0~1
Mean variance of logit error: var(logit error)	0.3719
Mean logit: $logit_m$	-0.8318
Mean temperature: Δt_m	-0.1
Residual of Δt	0.94
Notes: Steps in obtaining the adjusted equation	
Equation for regression coefficient	b=cov(Δt, logit)/var(logit)
Therefore, the equation for covariance	cov (Δt, logit)=b×var(logit)
Equation for logit error	var(logit error)= 1/{np(1−p)}
Adjusted value of b	b=cov(Δt, logit)/{var(logit) −var(logit error)}
The adjusted equation	Δt =1.028logit+c
Therefore, the equation for logit	logit=0.973Δt +c
The equation must pass through the Δt_m and the $logit_m$	c=$logit_m$−0.973Δt_m
The centre line of the deadband	logit=0.973Δt −0.7
The width of deadband	±1.5SD×Residual of Δt
The equations for deadband margins	logit=0.973(Δt±1.4) −0.7
The proportion of windows open	$p=e^{(logit)}/\{1+e^{(logit)}\}$

3.4.3 Quantification of constraints

Realistic knowledge of window-opening is needed to predict the thermal comfort and energy use in buildings. If controls such as windows are effective and easy to use, thermal discomfort can be greatly mitigated. In practice there may be constraints that hinder the use of such controls. In any thermal simulation these constraints need numerical values. We explore the nature and extent of these constraints operating on the use of windows using the method already reported (Rijal et al. 2011; 2012). We have reckoned all constraints from the relevant comfort temperature.

Table 10 shows considerable variation in the constraints from building to building. The results showed that constraints of window opening in the houses is smaller than that of the office buildings (Rijal et al. 2012). The reason might be that residents are free to open the windows in their homes, and thus the constraint might be small than that of the office buildings. However, further research is required to arrive at a completely acceptable conclusion.

The maximum constraint is 4.8 K which is smaller than that of Europe (5.2 K) and Pakistan (7.5 K). From the thermal comfort view point, people normally tolerate departures of some 2 K (Rijal et al. 2011). In more than 50% of the investigated houses it exceeded 2 K for windows open. It is interesting to note that there is no constraint for windows closed. A constraint of 2 K is normal and unlikely to result in discomfort, while constraints of around 5 K would indicate a significant problem with use of that control, while a constraint of around 8 K would render the control redundant for controlling the thermal environment.

Table 10 Constraints for each house

Building	Constrain (K)	
	Closed	Open
A1	-0.5	**3.3**
A2	-1.9	**4.7**
A3	-0.8	**3.6**
A4	-0.8	**3.6**
A5	0.0	**2.8**
A6	1.0	1.8
A7	0.0	**2.8**
A8	-1.7	**4.5**
A9	1.3	1.5
A10	0.6	**2.2**
B1	0.3	**2.5**
B2	-0.6	**3.4**
B3	1.7	1.1
B4	1.3	1.5
B5	0.5	**2.3**
B6	0.3	**2.5**
B8	0.1	**2.7**
B9	-1.1	**3.9**
B10	1.1	1.7
C1	-1.0	**3.8**
C2	1.3	1.5
C3	1.6	1.2
C4	0.9	1.9
C5	0.6	**2.2**
C6	1.4	1.4
C7	0.8	**2.0**
C8	1.1	1.7
C9	0.4	**2.4**
C10	2.0	0.8
Max.	2.0	4.7
Mean	0.3	2.5

Bold: those whose absolute value exceeded 2 K

4. Conclusions

We have investigated the window opening behaviour and corresponding thermal environment in living rooms in Gifu region of Japan for one year and the following results were found:

1. The proportion of the window opening in the naturally ventilated mode is significantly higher than that of the air conditioned mode.
2. The window opening is related to the indoor and outdoor air temperature in the naturally ventilated mode.
3. The window opening behaviour is predicted based on indoor and outdoor air temperature using logistic regression analysis. The predicted window opening matched well with that of the measured value.
4. The deadband of window opening in the investigated houses is 1.4 K which is smaller than the European and Pakistan office buildings. The results indicate that people are more liberal to open windows in their homes as compared to the users of office buildings.
5. The maximum constraint of window opening in the investigated houses is 4.8 K which is smaller than European and Pakistan office buildings.

Acknowledgements

We would like to thank to Mr. Shigemoto Hayashi of Maruhei Construction Co., Ltd. for data collection and Dr. Madhavi Indraganti for editing the paper. The models for window opening and closing were developed in collaboration with Prof. Michael Humphreys and Prof. Fergus Nicol during research at Oxford Brookes University.

References

Asawa T., Umehoshi N., Takezawa T., Shimizu T. (2005), Analysis of the behavioral characteristics of both window opening and air conditioning use at detached houses: relationship between outdoor microclimate and residents' living open to outdoor part 2, *J. Environ., Eng., AIJ, No. 593*, pp. 87-94.

Brager G.S., Paliaga G., de Dear R. (2004), Operable windows, personal control, and occupant comfort. ASHRAE Transactions, 110(2): 17-33.

Dick J.B. & Thomas D.A. (1951), Ventilating research in occupied houses. *JIHVE 19*, 306-326.

Griffiths I.D. (1990). Thermal comfort in buildings with passive solar features: Field studies, Report to the Commission of the European Communities, EN3S-090, UK.

Haldi F., Robinson D. (2010), On the unification of thermal perception and adaptive actions. *Building and Environment*, 45(11): 2440-2457.

Honjou M., Rijal H.B., Kobayashi R., Nakaya T. (2012), Investigation of comport temperature and adaptive model in Japanese houses, *Proceedings of 7th Windsor Conference: The changing context of comfort in an unpredictable world* Cumberland Lodge, Windsor, UK, 12-15 April 2012. London: Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Humphreys M.A., Rijal H.B. and Nicol J.F. (2010), Examining and developing the adaptive relation between climate and thermal comfort indoors. Proceedings of Conference: Adapting to Change: New Thinking on Comfort Cumberland Lodge, Windsor, UK, 9-11 April 2010. London: Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Kim J., Kawaguchi T., Tanabe S. (2009), The behavioral characteristic of office workers use of natural ventilation window, *J. Environ. Eng., AIJ, Vol. 74, No. 643*, pp. 1075-1082.

Kubo T. (2007), A field survey on usage of air-conditioners and windows in apartment houses in Johor Bahru city, *J. Environ. Eng., AIJ, No. 616,* pp. 83-89.

Majima M., Umemiya N., Yoshida H., Rijal H.B. (2007), Thermal comfort of traditional narrow alleys in an urban area, *J. Environ., Eng., AIJ, No. 622*, pp. 41-48.

McCartney K.J., Nicol J.F. (2002), Developing an adaptive control algorithm for Europe, *Energy and Buildings*, 34 (6): 623-635.

Nicol F., Jamy G.N., Sykes O., Humphreys M., Roaf S., Hancock M. (1994), A survey of thermal comfort in Pakistan toward new indoor temperature standards, Oxford Brookes University, Oxford England.

Nicol J.F., Humphreys M.A. (2004), A stochastic approach to thermal comfort – occupant behavior and energy use in buildings. *ASHRAE Transactions*, 110(2): 554-568.

Oseland N. (1995), predicted and reported thermal sensation in climate chambers, offices and homes. *Energy and Buildings* 23(2) 105-116.

Rijal H.B., Tuohy P., Humphreys M.A., Nicol J.F., Samuel A., Clarke J. (2007), Using results from field surveys to predict the effect of open windows on thermal comfort and energy use in buildings, *Energy and Buildings, 39(7)*: 823-836.

Rijal H.B., Tuohy P., Humphreys M.A., Nicol J.F., Samuel A., Raja I.A., Clarke J. (2008), Development of adaptive algorithms for the operation of windows, fans and doors to predict thermal comfort and energy use in Pakistani buildings. *ASHRAE Transactions, 114 (2)*: 555-573.

Rijal H.B., Tuohy P., Nicol F., Humphreys M.A., Samuel A. and Clarke J. (2008a), Development of an adaptive window-opening algorithm to predict the thermal comfort, energy use and overheating in buildings, *Journal of Building Performance Simulation 1 (1)*, pp. 17-30.

Rijal H.B., Humphreys M.A., Nicol J.F. (2009), Understanding occupant behaviour: the use of controls in mixed-mode office buildings. *Building Research and Information, 37 (4)*: 381-396.

Rijal H.B., Tuohy P., Humphreys M.A., Nicol J.F., Samuel A. (2011), An algorithm to represent occupant use of windows and fans including situation-specific motivations and constraints. *Building Simulation, 4 (2)*: 117-134.

Rijal H.B., Tuohy P., Humphreys M.A., Nicol J.F., Samuel A. (2012), Considering the impact of situation-specific motivations and constraints in the design of naturally ventilated and hybrid buildings, *Architectural Science Review 55(1)*, 35–48.

Robinson D., Haldi F. (2008), An integrated adaptive model for overheating risk prediction. *Journal of Building Performance Simulation*, 1 (1): 43-55.

Suzuki T., Umemiya N., Yoshida H. (2002), Structure of the causes of window opening and closing behavior from summer to autumn, *J. Archit. Plann. Environ. Eng., AIJ, No. 556*, pp. 91-98.

Umemiya N., Yoshida H. (2004), Survey on relationship between the ratio of window-opening area and the indoor and outdoor climate mainly for the season of natural ventilation, *Transaction of Air-Conditioning and Sanitary Engineers of Japan, No. 92*, pp.19-28.

Yun G.Y., Steemers K. (2007), Time-dependent occupant behaviour models of window control in summer. *Building and Environment*, 43(9): 1471-1482.