Study on Window Opening Algorithm to Predict Occupant Behaviour in Japanese Houses

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We investigated window opening behaviour and the thermal environment over a period of more than 3 years in the living rooms and bedrooms of dwellings in the Kanto region of Japan. We collected over 32,000 data-samples from 243 residents of 121 homes. The proportion of 'open window' in the free running mode is significantly higher than that in the cooling and heating modes. The window opening is related to the indoor or outdoor air temperature. Window opening behaviour as predicted by logistic regression analysis is in agreement with the measured data. These findings can be applied to develop an adaptive algorithm for window opening behaviour in Japanese residences.

1. Introduction

Natural ventilation from opening windows has been decreasing in houses in recent years because of the increasing prevalence of mechanical ventilation and air-conditioning. However, temperature control by opening and closing windows can reduce environmental impact by minimizing the period of the year when air-conditioning is needed.

There has been more research into window-opening behaviour in offices (Rijal et al. 2007, Yun & Steemers 2007, Robinson & Haldi 2008, Kim et al. 2009, Haldi & Robinson 2010) and university buildings (Suzuki et al. 2002, Umemiya & Yoshida 2004) than in dwellings (Dick & Thomas 1951, Asawa et al. 2005, Kubota 2007, Rijal et al. 2013). The findings from research in offices and universities cannot be assumed to apply to dwellings, where people's behaviour is less constrained. There is evidence that people respond differently in their own homes for a number of reasons, social, economic and cultural (Oseland, 1995). Thus it was necessary to conduct research also on residential window opening behaviour.

To explore window opening behaviour and develop a window opening algorithm for Japanese residences, thermal measurements were made and an occupant behaviour surveys conducted over a period of more than 3 years in the living rooms and bedrooms of dwellings in the Kanto region of Japan.

2. Methodology

Thermal comfort surveys and thermal measurements 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 can be found in Rijal et al. (2014). Indoor air temperature and relative humidity were measured in the living rooms and bedrooms, away from direct sunlight, at ten minute intervals using a data logger. The globe temperature was also measured in the living room in surveys 3, 4 & 5. Outdoor air temperature and relative humidity were obtained from the nearest meteorological station.

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 bedrooms ("before go to bed" and "after wake-up from the bed"). The window opening behaviour was recorded in binary form (0 = window closed, 1 = window open). We have collected over 32,000 samples.

Table-1 Description of survey

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

L: Living room, B: Bedroom, T_i: Indoor air temp. (℃), RH_i: Indoor relative humidity (%), T_g: Indoor globe temp. (℃), *: T_g is measured only in the living room.

3. Results and discussions

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.

3.1 Distribution of temperatures during voting

The mean outdoor air temperatures during the voting were 19.5 ℃, 27.6 ℃ and 7.2 ℃ for FR, CL and HT modes respectively (Rijal et al. 2014). The mean indoor air temperatures at the time of voting were 24.2 ℃, 27.3 ℃ and 19.2 ℃ 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 seasonal difference of the indoor air temperature is quite large, and that the data represent a wide range of outdoor temperature (Fig. 1).

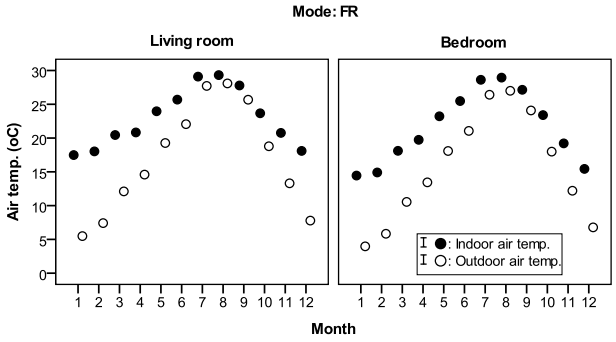

Figure-1 Monthly mean temperatures in FR mode (at 95% confidence level).

3.2 Evaluation of window opening behaviour

(1) Status of window opening (WO)

To understand the window opening behaviour, the mean proportions of 'window opening (WO)' are compared. The mean WO is 0.39, 0.03 and 0.00 for FR, CL and HT modes respectively. The mean window opening in living room is higher than in the bedroom. 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 window opening 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 value and lower than the UK value. We shall limit the analysis to the FR mode.

(2) Season, month and time of the day

The proportion of open windows (WO) is highest in summer and lowest in winter (Fig. 2.). 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 in the spring (Fig. 2(b)).

Evidently, the proportion of open windows gradually increases towards the summer months (Fig. 3). Conversely, it gently decreases towards the winter months as indoor or outdoor air temperature varies (Fig. 1).

The data were divided into four groups, in ascending order of time. Interestingly, the proportion of open windows gradually increases during the morning, and then decreases towards the evening (Fig. 4(a)). Most of occupants open the windows in the morning and shut them at night. These trends are similar for all seasons (Fig. 4(b)).

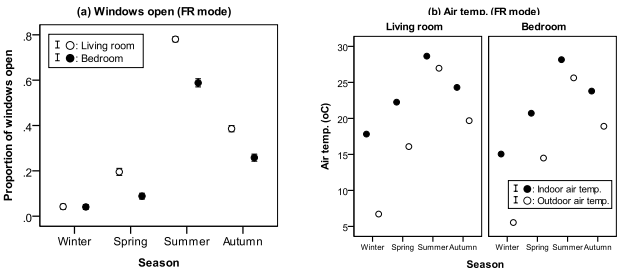

Figure-2 The proportion of open windows, indoor and outdoor air temperature in each season (at 95% confidence level).

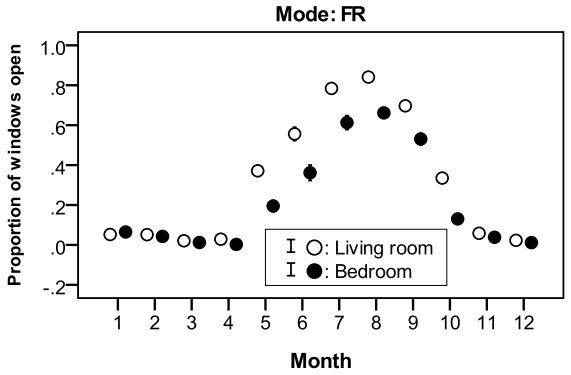

Figure-3 The proportion of open windows in each month (at 95% confidence level)

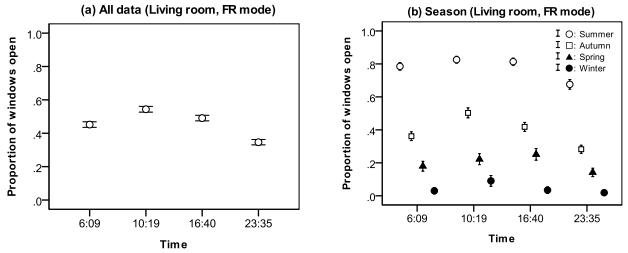

Figure-4 Proportion of open windows at 95% confidence intervals of time of day in living room.

(3) Relationship between the open windows & air temp.

In FR mode the open window correlated better with the outdoor temperature than with the indoor temperature (Table 2). The correlation coefficient for the living room is higher than for the bedroom. From these observations, it can be inferred that the window opening is related to both indoor and outdoor air temperatures.

The data were divided into ten groups, in an ascending order of temperature. The proportion of the window opening rises as the indoor globe or outdoor air temperature rises (Fig. 5). The proportion of window opening in the living rooms is higher than in the bedrooms. When mean indoor air temperature is 27.1 °C, the proportion of open windows is 0.63 in living room and 0.51 in bedroom (Fig. 5(a)).

When the mean outdoor air temperature is 24.3 °C, the proportion of windows open is 0.71 in living rooms and 0.58 in the bedrooms (Fig. 5(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). This is perhaps because the indoor and outdoor air temperature in Japan and Pakistan are considerably higher than that in the UK.

Table-2 Correlation coefficients in FR mode

Room	Items	Window: T_i	Window: T_o	T_i: T_o
Living room	r	0.58	0.62	0.87
	N	13,289	13,382	13,352
Bedroom	r	0.46	0.5	0.89
	N	8,946	9,000	8,997
All	r	0.53	0.58	0.88
	N	22,235	22,382	22,349

r: Correlation coefficient , N: Number of samples, T_i : Indoor air temp. (°C), T_o : Outdoor air temp. (°C), All correlations are significant ($p<0.001$)

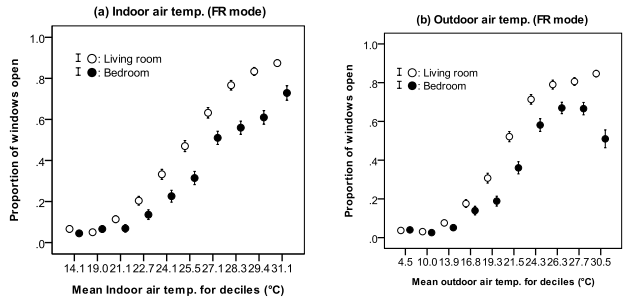

Figure-5 Proportion of open windows with 95% confidence intervals at deciles of temperatures.

3.3 Potential of the open window

The potential of the open window is further analyzed in the context of indoor and comfort temperatures. The mean indoor air temperature for the window open condition is 27.7 °C in the living room which is significantly higher by 5.3 K, than for the window closed condition (Fig. 6(a)). In UK office buildings, the mean globe temperature for the window open condition 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. In winter, the mean indoor air temperature for the 'open window' case is significantly lower than that of the 'closed window' case. The results showed that window opening is an effective way to control the indoor thermal environment.

The comfort temperatures were obtained by the Griffiths' method using the regression coefficients of 0.50 (Rijal et al. 2014). The mean comfort temperature for window open is 26.5 °C in living room which is 3.7 K higher than that of the case of window closed (Fig. 6(b)). 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. The temperature difference is highest in autumn. In winter the mean comfort temperature for the open window condition is significantly lower than for the window closed condition. The results showed that window opening is effective to create the comfortable thermal environment.

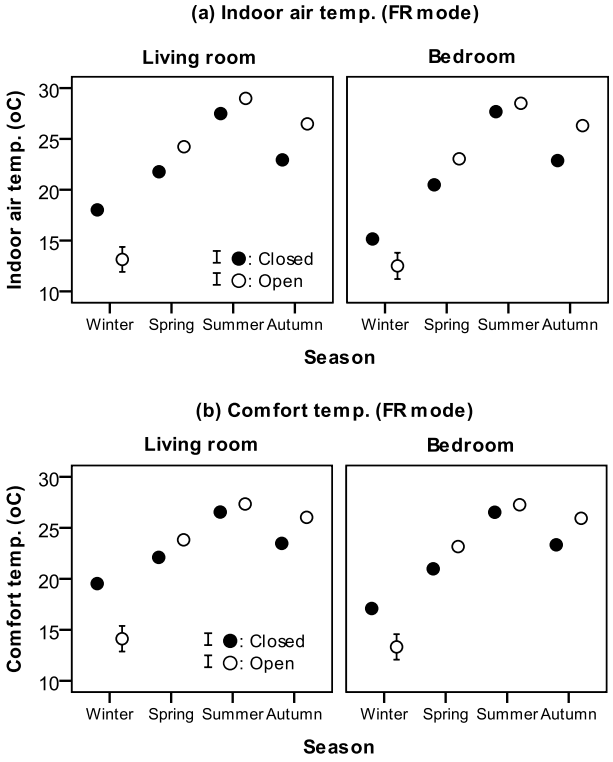

Figure-6 Seasonal variation of indoor air temperature and comfort temperature for windows open and closed in FR mode.

3.4 Development of an algorithm to predict window opening behaviour

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 (Rijal et al. 2013). 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. We have adopted the same method here, using SPSS version 19 for the calculations. The following regression equations were obtained for all data in between the windows open and the indoor or outdoor air temperature:

Living room

$\text{logit}(p)=0.394T_i - 10.144$

(n=13,289, R^2=0.34, S.E.=0.007, p<0.001) (1)

$\text{logit}(p)=0.372T_g - 9.659$

(n=9,833, R^2=0.29, S.E.=0.008, p<0.001) (2)

$\text{logit}(p)=0.258T_o - 5.675$

(n=13,382, R^2=0.38, S.E.=0.004, p<0.001) (3)

Bedroom

$\text{logit}(p)=0.291T_i - 8.100$

(n=8,946, R^2=0.24, S.E.=0.008, p<0.001) (4)

$\text{logit}(p)=0.206T_o - 5.113$

(n=9,000, R^2=0.26, S.E.=0.005, p<0.001) (5)

All data

$\text{logit}(p)=0.349T_i - 9.235$

(n=22,235, R^2=0.30, S.E.=0.005, p<0.001) (6)

$\text{logit}(p)=0.238T_o - 5.466$

(n=22,382, R^2=0.34, S.E.=0.003, p<0.001) (7)

T_i: Indoor air temperature (°C), T_g: Globe temperature (°C), T_o: Outdoor air temperature (°C), n: sample size, S.E.: Standard error, p: Significance level of the regression coefficient, R^2: Cox and Snell R^2.

A regression coefficient of 0.349 is obtained when the indoor air temperature is the predictor. This is higher than that obtained when the outdoor air temperature is used. In the Gifu region of Japan (Rijal et al. 2013), regression coefficients of 0.248 and 0.210 respectively were obtained with indoor or outdoor temperature. In Pakistan (Rijal et al. 2008) and in UK (Rijal et al. 2007) studies, regression coefficients of 0.176 and 0.354 respectively were obtained with indoor globe temperature is the predictor. In Kyoto (Majima et al. 2007) and UK (Rijal et al. 2007) data returned the regression coefficients of 0.119 and 0.181 respectively with outdoor air temperature is the predictor. The regression coefficient in the living room is slightly higher than the bedroom. The predicted window opening is well matched with measured values (Fig. 7).

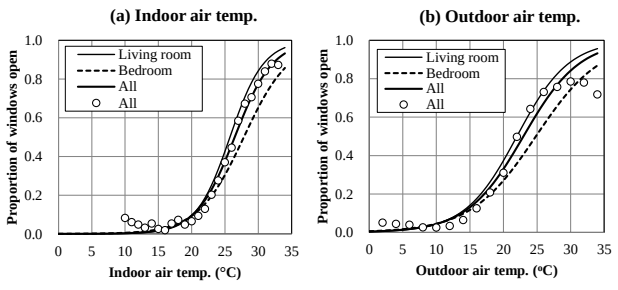

Figure-7 Comparison of measured (open circular dots) and predicted value (curved line) in NV mode. Measured values were grouped for every 1 °C for indoor air temperature and for every 2 °C for outdoor air temperature. The grouped data for samples less than 100 are not shown.

4. Conclusions

We have investigated the window opening behaviour and corresponding thermal environment over a period of more than 3 years in the living rooms and bedrooms of dwellings in the Kanto region of Japan and the following results were found:

1. The proportion of the window opening in the free running mode is significantly higher than that of the cooling or heating modes.
2. The window opening is related to the indoor and outdoor air temperature in the free running 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.

Acknowledgments

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