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Development of a window opening algorithm based on adaptive thermal comfort to predict occupant behavior in Japanese dwellings

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Abstract

Window opening behavior and thermal comfort were monitored in relation to the thermal environment over a 4 year period in the living rooms and the bedrooms of dwellings in the Kanto region of Japan. 36 144 sets of physical and subjective data were collected from 243 residents of 120 dwellings. This paper explores relationships between the different variables in the data. The likelihood of windows being open depended on the three modes of operation of the dwelling, free running (FR), heating (HT) or cooling (CL). In the FR mode, the likelihood was much higher than in either the CL or the HT modes. The likelihood that a window is open correlated well with both indoor temperature and outdoor air temperature in the FR Mode. The indoor comfort temperature correlated well with the running mean of the outdoor temperature. Window opening behavior as predicted by logistic regression analysis is in agreement with the measured data. The deadband of window opening was narrower, and the constraint on window opening was smaller than had previously been found in studies in office buildings. Equations are given to quantify these relations and to enable window opening and comfort temperature to be predicted from outdoor temperature.

Keywords
comfort temperature, constraint, deadband, dwellings, window opening

1. Introduction

People use various “adaptive opportunities” to control their indoor thermal environment. One such opportunity is the opening of a window. This is an important action people use to achieve and maintain indoor thermal comfort. In Japanese office buildings, the indoor thermal environment is often controlled using mechanical air conditioning. In dwellings the same effect is more often obtained through window opening, avoiding a direct energy cost to the household. However, natural ventilation obtained from opening windows has become less common in dwellings because of the increasing use of mechanical ventilation and air-conditioning. Temperature change using window opening can reduce environmental impact by reducing the use of air conditioning as much as possible.

People at home usually adjust their own thermal environments. Models relating the behavior of the occupants to the climate and culture are an addition to our knowledge of human adaptive behavior. Knowing how likely people are to open windows in various seasons also helps the correct sizing of air cooling and heating plant—oversized plant is usually less efficient and more costly. Window opening is an effective way to reduce the indoor air temperature,[1] and reduce the maximum heat load, especially in summer. For the free-running mode of operation, the question is: can this proposed design provide the required indoor temperatures? If thermal simulation or experience suggests that it cannot, then the design will need to be changed, particularly with regard to windows, shading, and thermal mass so that thermal comfort is more likely to be achievable. Thermal simulation packages often assume a fixed schedule of window opening,[1] so more realistic data on window opening behavior will help to improve the thermal simulations and a window opening algorithm becomes a useful passive design tool.

A number of projects have researched window opening behavior in offices,[1-11] university buildings,[12,13] and dwellings.[14-21] It is well-known that residents behave differently in their own dwellings for social, economic, and cultural reasons.[22] The findings from research conducted in workplaces cannot therefore be assumed to apply to dwellings, where the behavior of people may be subject to fewer constraints. Similarly results from one region of the world cannot be assumed to apply to another where there is a different culture and building design. Consequently, the window

Table 1. Description of the field survey

Survey	Survey period		Room	Measured variables*	Dwellings	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	3300	2558
2	05-8-2011	06-9-2011	Living	T_i, RH_i	59	52	57	109	2861	-
3	21-7-2011	08-5-2012	Living, Bed	T_i, RH_i, T_g	10	11	12	23	463	984
4	25-7-2012	24-6-2013	Living, Bed	T_i, RH_i, T_g	30	26	28	54	13 083	7061
5	10-8-2013	09-8-2014	Living, Bed	T_i, RH_i, T_g	10	14	14	28	2679	3125
Total					120	119	125	244	22 386	13 728

T_i: Indoor air temp. (°C); RH_i: Indoor relative humidity (%); T_g: Indoor globe temp. (°C). *T_g was measured only in the living room.

opening algorithm developed for office buildings[7] may not apply to Japanese dwellings and research about window opening in Japanese dwellings was needed.

To explore window opening behavior and develop a window opening algorithm for Japanese dwellings, thermal measurements were made, and occupant behavior surveys were conducted for 4 years in the living rooms and bedrooms of dwellings in the Kanto region of Japan.

2. Materials and methods

2.1 The field surveys

The surveyed dwellings were detached houses and apartments typical of Japanese urban areas. They have air conditioning to provide heating in cold weather and cooling in hot weather. Table 1 lists the times and location of the five field surveys. Records were collected of thermal comfort, occupant behavior, and thermal conditions from occupants of 120 dwellings in the Kanto region (Kanagawa, Tokyo, Saitama, and Chiba) over a 4-year period (2010-2014).[23,24] Survey 2 was conducted for 1 month, and the other surveys were conducted over a full year. Indoor air temperature, globe temperature, and relative humidity were measured in the living rooms and bedrooms, away from direct sunlight, at 10-minute intervals using a digital data logger (Figure 1, Table 2). Figure 1 shows a living room with instrumentation. Outdoor air temperature and outdoor relative humidity were taken from the nearest meteorological station.

Figure 1. Details of the thermal measurement

Table 2. Description of the instruments

Parameter measured	Trade name	Range	Accuracy
Air temperature, humidity	TR-74Ui	0-55°C, 10%-95% RH	±0.5°C, ±5%RH
Globe temperature	Tr-52i SIBATA 080340-75	−60 to 155°C Black painted 75 mm diameter globe	±0.3°C

The number of subjects was 119 males and 125 females. They completed a Japanese-language paper questionnaire, up to four times a day in the living room and twice a day in the bedroom ("before going to bed" and "after waking up from the bed"). The modified thermal sensation vote (mTSV) shown in Figure 2 was used to evaluate the thermal sensation. Both numbering and words of mTSV scale were shown on the questionnaire. Window opening was recorded in binary form by the occupant at the time of completing the questionnaire (0 = window closed, 1 = window open) (Figure 2). In total 36 144 survey questionnaires were completed.

2.2 The modes of operation

Generally, Japanese dwellings can be classified as change-over mixed-mode buildings.[25] This means they can use air conditioning to provide both cooling in summer and heating in winter. The data were divided into three groups: the FR mode (free running, where the air conditioning was not in use at the time of the survey), CL mode (cooling by air conditioning), and HT mode (heating). A weakness in this classification procedure is that there is no record of whether heating or cooling had been in use before the questionnaires were completed, so that the "free running" mode may include some instances where the heating or cooling had only just been turned off, so they should more properly be allocated to the heating or to the cooling mode. The numbers of such instances are assumed to be small.

2.3 Estimating the comfort temperature

Comfort temperatures (the estimated temperature corresponding to "neutral" on the scale) were obtained from the votes on the mTSV scale using the Griffiths' method.[3,26-29]

$$T_c = T_i + (4 - \text{mTSV})/\text{a}^* \quad (1)$$

T_c is the estimated comfort temperature using the Griffiths' method (°C), T_i is the indoor air temperature (°C), and a* is the assumed coefficient of dependence of the vote on the room temperature. In this analysis a* is taken to be 0.50 votes per degree K, as found from analyses of field-study data worldwide[30] and from Japan.[31]

Questionnaire of living room

Date: ____ **Name:** ____ **Voting time ⇨**

	1st	2nd	3rd	4th
Hour				
Min.				

How do you feel now?

1 Very cold — 2 Cold — 3 Slightly cold — 4 Neutral (neither cold nor hot) — 5 Slightly hot — 6 Hot — 7 Very hot

Please write 0 or 1 for adjustment condition now in living room.

	0	1	1st	2nd	3rd	4th
Window	0 Closed	1 Open				
Internal door	0 Closed	1 Open				
Cooling	0 Off	1 On				
Heating	0 Off	1 On				
Fan	0 Off	1 On				

Figure 2. Questionnaire for the thermal comfort survey and occupant behavior surveys. (Extracted from the full questionnaire and translated into English.)

2.4 Logistic regression analysis

To estimate the proportion of windows open, logistic regression analysis was conducted.[32] The relationship between the probability of windows being open (p) and the indoor or outdoor temperature (T) is of the form:

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

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

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

3. Results and discussion

3.1 Seasonal variation in temperature at the time of voting

Figure 3 shows the monthly mean outdoor and indoor air temperature for buildings in the FR mode in living rooms and bedrooms. Because of the large number of samples, the 95% confidence interval of the mean temperature (mean ± 2 SE) is very small. (This also applies to similar figures throughout this paper.) The figure shows the substantial seasonal variation in both indoor and outdoor temperature.

Table 3 shows the mean and standard deviation of the indoor air temperature, globe temperature, and outdoor air temperature at the time of voting in each mode. According to the Japanese Act,[34] the temperature range for performance halls, department stores, shops, offices, schools, apartment houses, etc. must be within the range 17-28°C. In 2005, the Japanese government introduced the "Cool Biz" and "Warm Biz" programs that recommend an indoor temperature of 28°C for cooling and 20°C for heating for energy saving and health or comfort.[35] The results show that the mean indoor temperatures during heating and cooling were quite close to these recommendations. The median of the indoor air temperature is 19.2°C for HT mode and 27.2°C for CL mode, and thus most indoor air temperatures are below the recommended values. The seasonal range of the mean indoor air temperature was some 15 K, and the seasonal range of mean outdoor temperature was some 20 K.

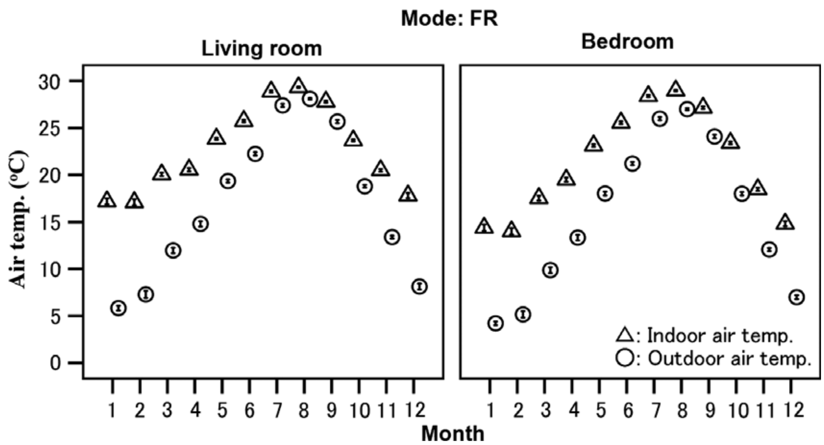

Figure 3. Monthly mean outdoor and indoor air temperature at the time of voting, with 95% confidence intervals (mean ± 2 SE)[33]

Table 3. Indoor and outdoor temperatures at the time of voting and proportion of open windows in various modes

		T_o (°C)			T_i (°C)			T_g (°C)			Window opening		
Mode	Room	N	Mean	SD	N	Mean	SD	N	Mean	SD	N	Mean	SD
FR	Living	14 599	20.0	7.7	14 508	24.5	4.7	11 012	23.5	4.5	14 602	0.44	0.50
	Bed	10 740	17.3	8.2	10 687	22.5	5.9	-	-	-	10 802	0.27	0.44
FR	All	25 339	18.9	8.0	25 195	23.7	5.3	-	-	-	25 404	0.37	0.48
CL	All	6802	27.6	2.7	6532	27.3	1.9	2951	27.6	1.7	6777	0.03	0.16
HT	All	3604	7.2	4.2	3582	18.9	2.9	2256	19.6	2.8	3671	0.00	0.04

T_o: Outdoor air temp.; T_i: Indoor air temp.; T_g: Indoor globe temp.; N: Number of observation; SD: Standard deviation.

3.2 Window opening behavior

3.2.1 Status of window opening

The means were calculated from the binary data (0 = window closed, 1 = window open) and are shown in Table 3. The result indicates that occupants did not open windows in the heating mode and very rarely did so in the cooling mode. Window opening in the living room is higher than in the bedroom.

We limit our analyses to the FR mode, because the windows in the other modes were so rarely open.

The mean window opening in these Japanese dwellings is close to the value for offices and commercial buildings in Pakistan[3] and much lower than the UK[1] office value.

3.2.2 Season, month, and time of the day

Seasonal and monthly differences in the proportion of windows open in FR mode are shown in Figure 4. The proportion gradually increases toward the summer months and then decreases toward the winter months (Figure 4B).

The data were then divided into quartiles, in ascending order of time of day. The proportion of windows open gradually increased during the morning and then decreased toward the evening (Figure 5A). These trends are similar for all seasons (Figure 5B) and are in agreement with the findings of previous research.[19] The proportion of windows open is generally lower in bedrooms than in living rooms.

3.2.3 Relationship between window opening and air temperature

Figure 6 shows the proportion of open windows and the corresponding temperatures. The data were divided into 10 groups (deciles) in an ascending order of temperature. The proportion of the windows open rises as the indoor or outdoor temperature rises. It was generally higher for living rooms than bedrooms at any particular temperature.

The proportion of windows open decreases at the highest outdoor temperatures. This trend was also observed in the Pakistan study.[3] Most likely, occupants closed windows to prevent excessively warm air entering in the room.

3.3 Cooling effect of the open window

3.3.1 Indoor air temperature

Opening a window provides mixing of indoor and outdoor air, and thus if it is cooler outdoors than indoors, opening a window reduces room temperature. Furthermore, as shown by other studies,[36] window opening is also related to air quality,

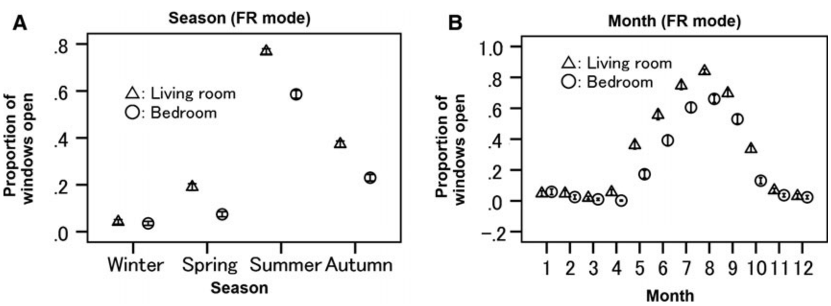

Figure 4. The mean proportion of open windows with 95% confidence intervals (mean ± 2 SE) in FR mode: (A) Season and (B) Month[33]

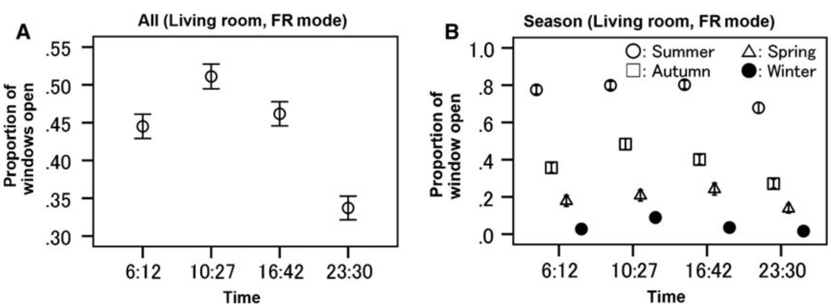

Figure 5. The mean proportion of open windows with 95% confidence intervals (mean ± 2 SE) for time of day in living rooms in FR mode: (A) All data and (B) Season

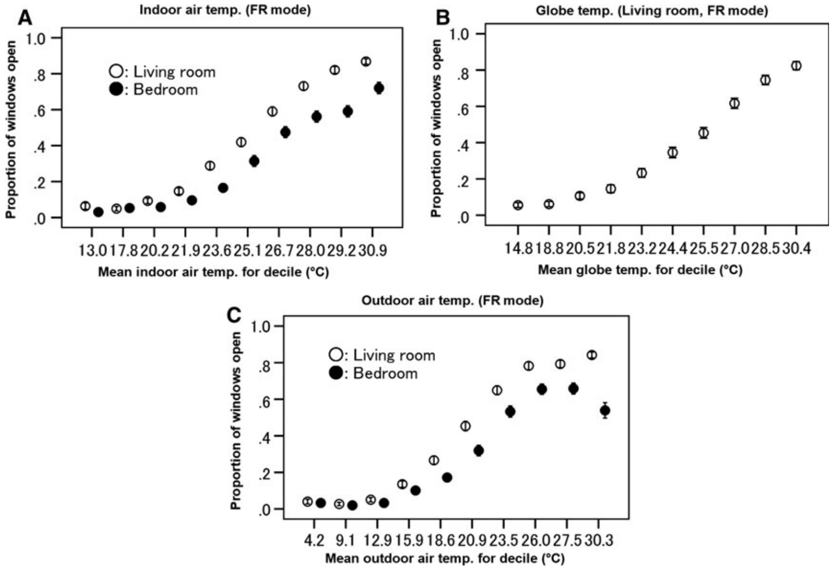

Figure 6. The mean proportion of open windows with 95% confidence intervals (mean ± 2 SE) at deciles of temperatures in FR mode: (A) Indoor air temperature, (B) Indoor globe temperature, and (C) Outdoor air temperature[33]

noise, air movement, and various social and cultural factors. In this section, we try to evaluate the cooling effect of window opening in each season.

Figure 7 shows the seasonal variation in indoor air temperature for cases when windows are open and closed. The mean indoor air temperature for the window open condition is 27.6°C in the living room and 27.1°C in the bedroom, which are higher by 5.5 K (t-value = −85.5, $P < .001$) and 6.4 K (t-value = −56.8, $P < .001$), respectively, than for the window closed condition. Thus, the temperature difference between the cases of open and closed windows in dwellings is higher than that of the UK office buildings.[4] This suggests that, rather than cooling the room,[4] the general result of opening the window in warm weather was to limit any rise in indoor air temperature that would have occurred had the window remained closed, and likewise in cool weather closing the window will prevent any uncomfortable temperature drop. Thus, the window is in effective way to control the indoor thermal environment.[1,3-7]

3.3.2 Comfort temperature and window opening

Window adjustment is an important way to control adaptive thermal comfort in buildings operating in FR mode. In this section, we consider how window opening is related to the manner in which the comfort temperature changes.

Figure 8 and Table 4 show the seasonal variation in comfort temperature with windows open and closed. The mean comfort temperature for windows open is 26.5°C in the living room, which is 4.0 K higher (t-value = −69.1, $P < .001$) than in the case of windows closed. This trend is higher than in office buildings.[37]

The comfort temperature is also shown in Figure 9 as a scatter-plot against the running mean of the outdoor temperature. The regression lines for windows open and closed are similar (within 1 K across the range of the running mean outdoor temperature), so a single regression line may be used to describe the relation:

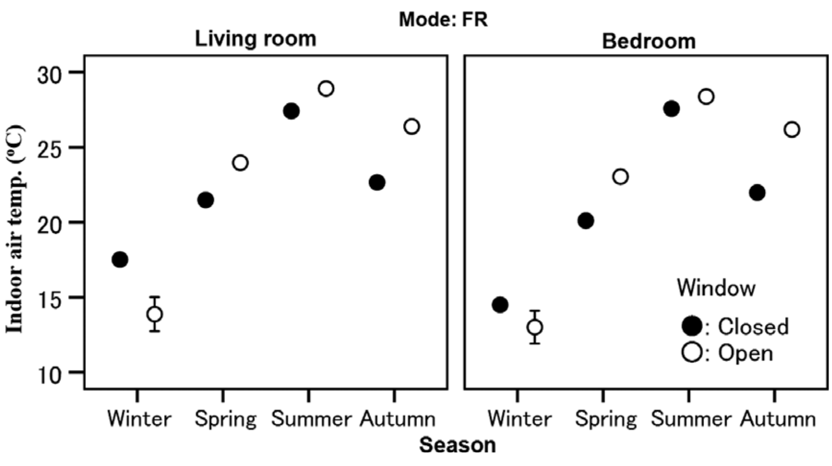

Figure 7. Seasonal variation in mean indoor temperature for windows open and closed in FR mode with 95% confidence intervals (mean ± 2 SE) in FR mode

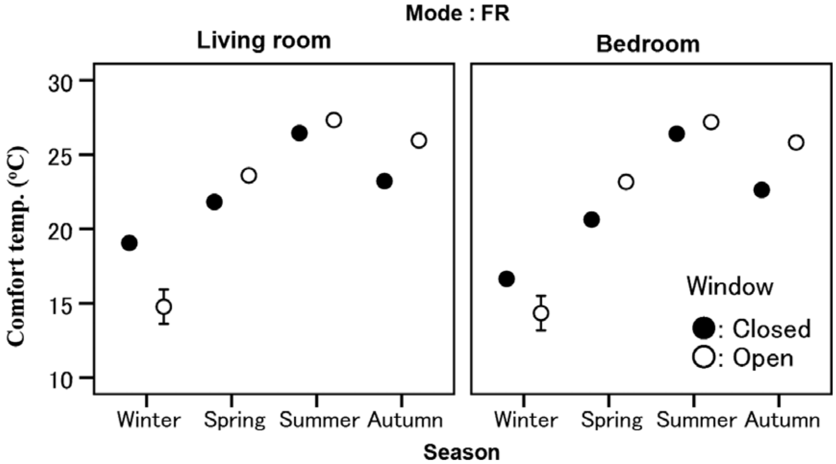

Figure 8. Seasonal variation in the mean comfort temperature for windows open and closed in FR mode with 95% confidence intervals (mean ± 2 SE) in FR mode[33]

$$T_c = 0.481T_{rm} + 14.3(n = 25,054, R^2 = 0.70, \text{S.E.} = 0.002, P < 0.001) \quad (4)$$

T_{rm}: the exponentially weighted running mean outdoor temperature for the day (°C)[31,38]; n: sample size; R^2: coefficient of determination; SE: standard error of the regression coefficient; P: significance level of the regression coefficient.

The equation is similar to that obtained from a worldwide database of surveys (Humphreys et al.[30], p. 308).

3.4 Development of equations to predict window opening

Our analysis is concerned solely with the temperature. Other possible influences on window opening behavior are humidity, air quality, external noise, and social and cultural factors (see e.g., Andersen et al.,[18,39] Fabi et al.[20,36]). The humidity is one of the major factors in characterizing Japanese climate, and could affect window opening behavior, particularly at high temperatures. Full modeling of window opening behavior would need to incorporate such additional factors.

3.4.1 Logistic regression curves

In this section, we use the data to quantify and predict window opening behavior in dwellings.[19] Such models are useful for the thermal simulation of dwellings.

Logistic regression equations using raw data were obtained for the relation between the "window-open" response and the indoor temperature, as well as for the outdoor air temperature.

Living room

$$\text{logit(p)} = 0.386T_i - 10.0(n = 14,435, R^2 = 0.34, \text{S.E.} = 0.007, P < 0.001) \quad (5)$$

$$\text{logit(p)} = 0.362T_g - 9.4(n = 10,979, R^2 = 0.29, \text{S.E.} = 0.008, P < 0.001) \quad (6)$$

$$\text{logit(p)} = 0.257T_o - 5.7(n = 14,526, R^2 = 0.38, \text{S.E.} = 0.004, P < 0.001) \quad (7)$$

Bedroom

$$\text{logit(p)} = 0.302T_i - 8.4(n = 10,633, R^2 = 0.26, \text{S.E.} = 0.007, P < 0.001) \quad (8)$$

$$\text{logit (p)} = 0.216T_o - 5.3(n = 10,686, R^2 = 0.28, \text{S.E.} = 0.005, P < 0.001) \quad (9)$$

Table 4. Comfort temperatures for windows open and closed

		Comfort temperature T_c (°C)									
		Living room					Bedroom				
Season	Window	N	Mean	SD	*t*-value*	Open-closed	N	Mean	SD	*t*-value*	Open-closed
Winter	Closed	1484	19.1	2.8	14.6	−4.3	1762	16.7	3.3	7.1	−2.3
	Open	65	14.8	4.7			66	14.3	4.7		
Spring	Closed	2343	21.8	2.5	−14.9	1.8	2007	20.6	3.4	−8.1	2.5
	Open	551	23.6	2.3			167	23.2	2.6		
Summer	Closed	1163	26.5	2.0	−10.8	0.9	1331	26.4	2.1	−9.5	0.8
	Open	3843	27.3	2.1			1875	27.2	1.9		
Autumn	Closed	3136	23.2	2.9	−31.0	2.7	2619	22.6	3.6	−19.2	3.2
	Open	1846	26.0	2.7			796	25.8	3.1		
All	Closed	8126	22.5	3.5	−69.1	4.0	7719	21.4	4.6	−44.6	4.9
	Open	6305	26.5	2.8			2904	26.3	3.2		

*All open/closed temperature differences are statistically significant ($P < .001$).

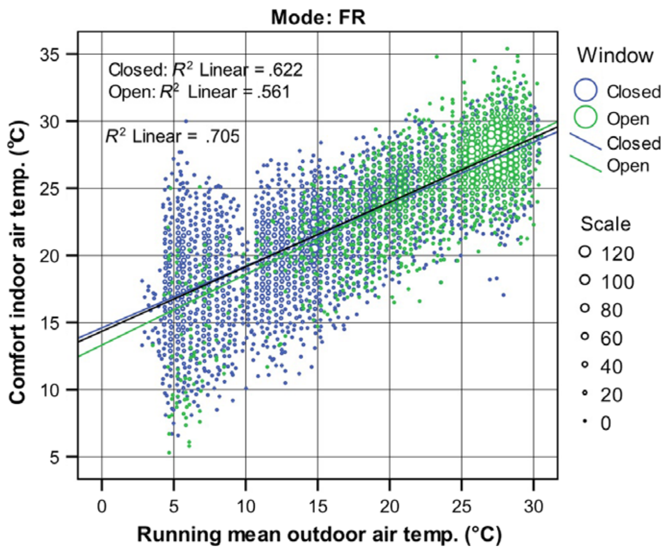

Figure 9. Scatter-plot of spot-estimates of comfort temperature against the exponentially weighted running mean outdoor air temperature (alpha = 0.80)

All data

$$\text{logit(p)} = 0.349T_{\text{i}} - 9.2(\text{n} = 25,068, R^2 = 0.32, \text{S.E.} = 0.005, P < 0.001) \quad (10)$$

$$\text{logit(p)} = 0.241T_{\text{o}} - 5.6(\text{n} = 25,212, R^2 = 0.35, \text{S.E.} = 0.003, P < 0.001) \quad (11)$$

T_i: Indoor air temperature (°C); T_g: Globe temperature (°C) (not recorded in bedrooms); T_o: Outdoor air temperature (°C); n: sample size; SE: standard error of the regression coefficient; P: significance level of the regression coefficient, and R^2: Cox and Snell R^2. [Note 1]

A logistic regression coefficient of 0.257 was obtained for living rooms, and a coefficient of 0.216 for bedrooms, when the outdoor air temperature is used as the predictor. These are in line with values from other studies (see Rijal et al.[1,3,19] and Majima et al.[40]).

These logistic relations transformed back to probabilities are shown in Figure 10. The predicted windows open is well matched with measured values, except when, as noted above, the outdoor temperature is very high when the windows are more likely to be closed. The proportion of windows open in the living rooms is higher than in the bedrooms. The relation is almost the same whether against indoor air temperature or globe temperature, and thus, the results can be presented using the indoor air temperature alone.

3.4.2 Difference between families who mostly, sometimes and rarely have their windows open

A previous study found that the proportion of windows open differs from person to person, such that some may be regarded as "active" in their use of windows while others may be regarded as "passive."[1] In this section, we also classify the data by how frequently the families have open windows. These are divided into (i) rarely (P_{wm} < 0.20), (ii) sometimes (0.20 ≤ P_{wm} < 0.70), and (iii) mostly (P_{wm} ≥ 0.70). These are classified by judging the mean window opening distribution of each family (P_{wm}). On this criterion there are 59, 39, and 20 families whose windows are mostly, sometime and rarely open in the database.

Those families which either leave there window open almost all the time, or alternatively almost never open them can be seen as "passive" in that they rarely respond to a changing temperature using the windows. Between these two are those 39 families who sometimes use their window. We obtained the following equations using logistic regression analysis for the three groups of families:

Mostly window opening families

$$\text{logit(p)} = 0.133T_{\text{i}} - 1.5(\text{n} = 3,742, R^2 = 0.04, \text{S.E.} = 0.011, P < 0.001) \quad (12)$$

$$\text{logit(p)} = 0.057T_{\text{g}} + 0.2(\text{n} = 499, R^2 = 0.02, \text{S.E.} = 0.019, P = 0.003) \quad (13)$$

$$\text{logit(p)} = 0.119T_{\text{o}} - 0.8(\text{n} = 3,748, R^2 = 0.05, \text{S.E.} = 0.008, P < 0.001) \quad (14)$$

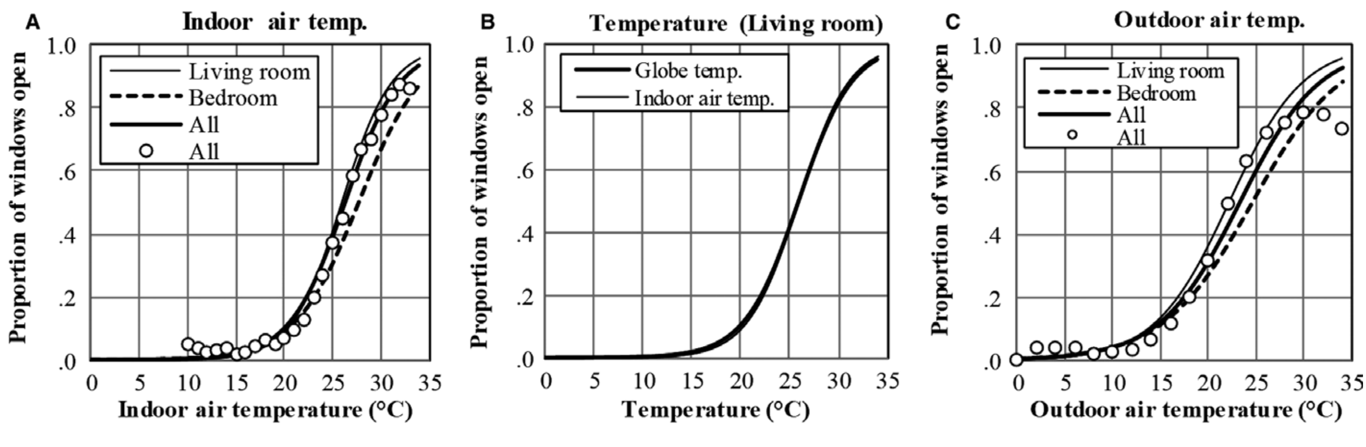

Figure 10. Relation between window opening behavior and temperature in the FR mode: (A) Indoor air temperature, (B) Indoor globe temperature and Indoor air temperature in the living room, and (C) Outdoor air temperature.[33] The figure compares the measured data (open circles) and the predictions (curves from the equations). (Measured values 1 K bins of indoor air temperature and 2 K of outdoor air temperature. Samples < 100 observations omitted)

Sometime window opening families

$$\text{logit(p)} = 0.346T_{\text{i}} - 8.8(\text{n} = 12,919, R^2 = 0.31, \text{S.E.} = 0.006, P < 0.001) \quad (15)$$

$$\text{logit(p)} = 0.444T_{\text{g}} - 10.8(\text{n} = 6,760, R^2 = 0.37, \text{S.E.} = 0.011, P < 0.001) \quad (16)$$

$$\text{logit(p)} = 0.251T_{\text{o}} - 5.5(\text{n} = 13,061, R^2 = 0.35, \text{S.E.} = 0.004, P < 0.001) \quad (17)$$

Rarely window opening families

$$\text{logit(p)} = 0.289T_{\text{i}} - 9.3(\text{n} = 8,407, R^2 = 0.10, \text{S.E.} = 0.012, P < 0.001) \quad (18)$$

$$\text{logit(p)} = 0.388T_{\text{g}} - 11.7(\text{n} = 3,770, R^2 = 0.15, \text{S.E.} = 0.020, P < 0.001) \quad (19)$$

$$\text{logit(p)} = 0.163T_{\text{o}} - 5.4(\text{n} = 8,403, R^2 = 0.10, \text{S.E.} = 0.006, P < 0.001) \quad (20)$$

These equations are plotted in the Figure 11. Not surprisingly the proportion of "mostly" window open families is considerably higher than that of the sometime and the "rarely" families is lower. When indoor or outdoor temperature is 26°C, the proportion of mostly window opening families is about 0.33 and 0.73 higher than the sometime and rarely window opening families, respectively. When the proportion of window opening is 0.50, the indoor and outdoor air temperatures for sometimes window opening families are 6.8°C and 11.3°C lower than that for the rarely window opening families, respectively. The "sometime" or "active" group shows a strong dependence of the proportion of windows open on the temperature suggesting that these families use the windows to regulate the indoor temperature between about 20°C and 30°C.

3.4.3 Deadband of temperature for window opening behavior

Indoor and outdoor air temperature

The relation between the proportion of windows open and the temperature are shown in Figure 12. The original regression line does not fit very well into the grouped data,[1] and thus it is further adjusted using the existing procedures (Table 5).[3,4,19,30]

83% of the points are within ±4.8 K range (±1.5 standard deviations) of the regression line (Figure 12A). The deadband is the same as for Japanese dwellings in Gifu,[19] bigger than that of the UK (2.1 K) and smaller than that of Pakistan (7.0 K).[3,4] The deadband (6.6 K) with respect to the outdoor temperature is bigger than that of the Japanese dwellings of Gifu (5.4K)[19] and UK (5.0 K) studies.[1]

Departure from comfort temperature

As we shown in the previous section, the width of the deadband for windows based on indoor air temperature is wider than had been found from the UK data,[1] probably because Japan has higher seasonal differences in comfort temperatures compared to the UK. Based on existing research, the fundamental or basic deadband can be estimated based on the temperature departure from the comfort temperature ($\Delta t = T_i - T_c$).[3,6,19] The following logistic regression equation using raw data was obtained for all data in between the windows open and the Δt:

$$\text{logit(p)} = 0.568\Delta t - 0.7(\text{n} = 25,054, R^2 = 0.17, \text{S.E.} = 0.010, P < 0.001) \quad (21)$$

Equation 21 is shown in Figure 13 as an original logistic regression line. However, the original line does not fit very well with the grouped data,[19] and thus it is adjusted using the existing procedures (Table 6).[3,19,30]

88% of the points are within ±1.8 K range (±1.5 standard deviations) of the regression line, which is bigger than that of the Japanese dwellings of Gifu (1.4 K) and smaller than that of the UK (2.0 K), Europe (2.3 K), and Pakistan (2.8 K).[6] This might be because there is less constraint in the use of windows in dwellings than there is in office buildings which will be discussed in next section.

3.4.4 Quantification of constraints

People may not be free to open the window because of the various constraints such as difficulty, pollution, noise, etc. In any thermal simulation these constraints need numerical values [7, 28 (Chapter 3), 30 (Chapter 31)]. We quantity the constraints on the window opening using the method already reported.[7,19]

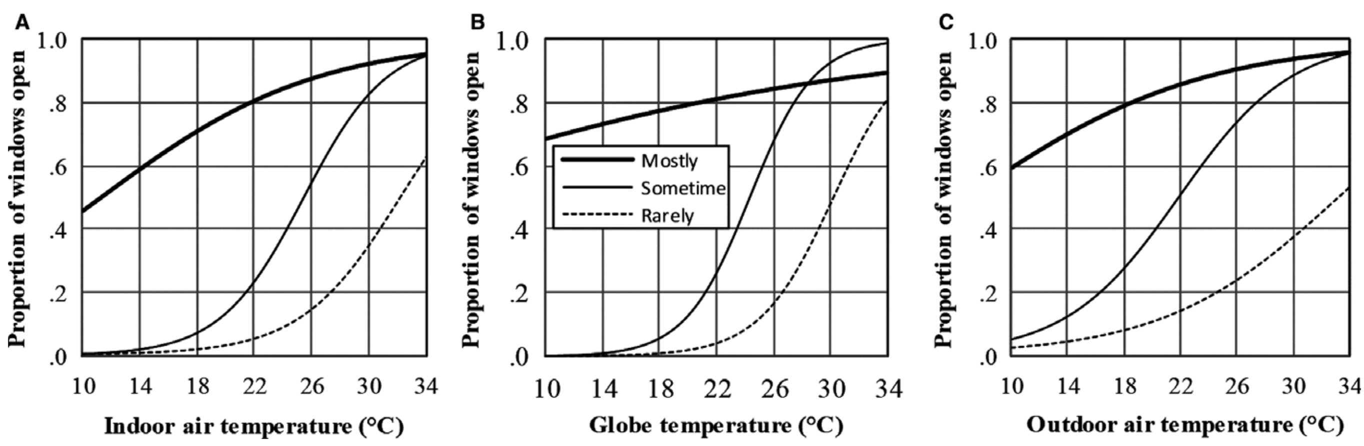

Figure 11. Relation between the families who use window opening mostly, sometime and rarely window opening in the FR mode: (A) Indoor air temperature, (B) Indoor globe temperature, and (C) Outdoor air temperature

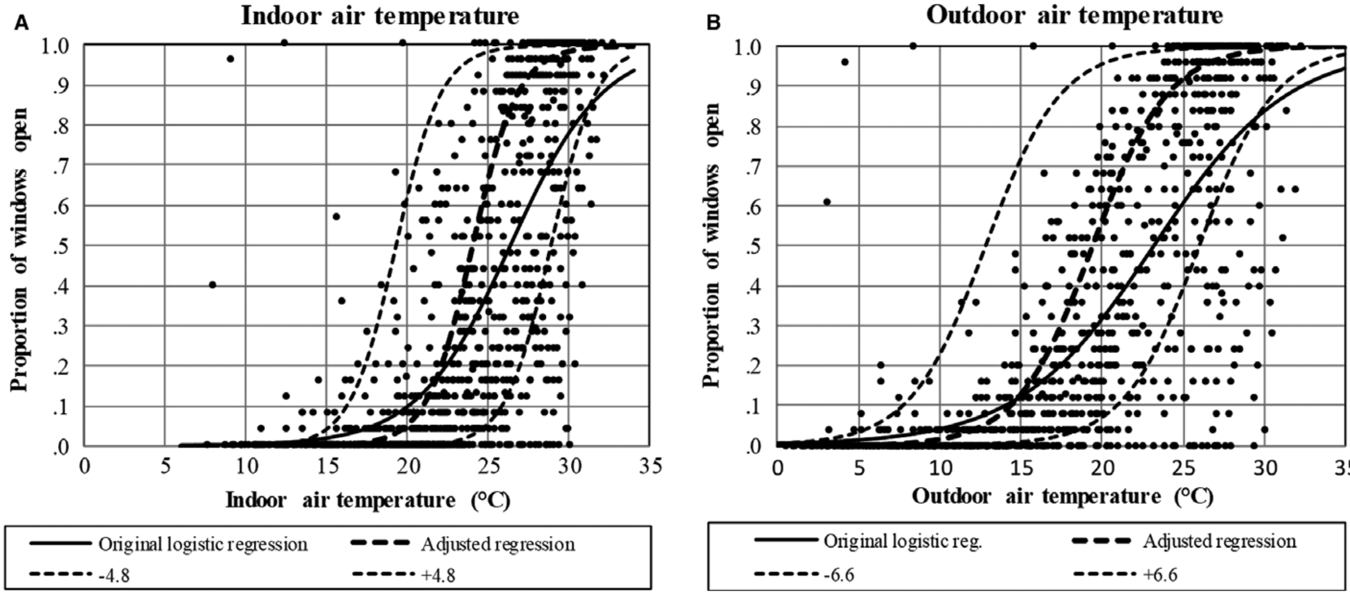

Figure 12. Logistic regression curves for open windows as a function of (A) indoor air temperature and (B) outdoor air temperature in all FR modes.[33] The three lines (left: closure from the open position, center, and right: closed to open position) are the deadband of windows open. Each data point is the mean of 25 sets of raw data observations at the given temperature

Table 5. Symbols and values of parameters used to calculate the adjusted regression equation for indoor and outdoor air temperature, based on the records grouped in 25 samples

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	1.226	2.034
Variance of logit: var(logit)	3.420	3.527
Covariance of T and logit: cov(T, logit)	4.193	5.503
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)	0.4228	0.4312
Mean logit: logit_m	−0.4949	−0.4527
Mean air temperature: T_m	23.4	18.4
Residual of T	4.8	6.6
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=1.399logit+c	T_o=2.317logit+c
Therefore, the equation for logit	logit=0.715T_i+c	logit=0.432T_o+c
The equation must pass through the T_m and the logit_m	c=logit_m−0.715T_m	c=logit_m−0.432T_m
The centerline of the deadband	logit=0.715T_i−17.2	logit=0.432T_o−8.4
The width of deadband	±1.5SD×Residual of T_i	±1.5SD×Residual of T_o
The equations for deadband margins	logit=0.715(T_i±4.8)−17.2	logit=0.432(T_o±6.6)−8.4
The proportion of windows open	$p=e^{(\text{logit})}/\{1+e^{(\text{logit})}\}$	

Table 7 shows the variation in the constraints in dwellings. The constraints on window opening in dwellings are smaller than that of office buildings.[7,19] The reason might be that people are freer to open the windows in their dwellings than they are in office buildings.

The maximum constraint is 5.1 K, which is bigger than that of the Japanese dwellings of Gifu (4.7 K) and smaller than that of offices in Europe (5.2 K) and Pakistan (7.5 K).[6,19] From the thermal comfort view-point, people normally tolerate departures of some 2 K.[7] In approximately 52% of the investigated dwellings, the constraint exceeded 2 K for windows open. These findings can be used in the thermal simulation to predict the window opening behavior and energy use in dwellings.

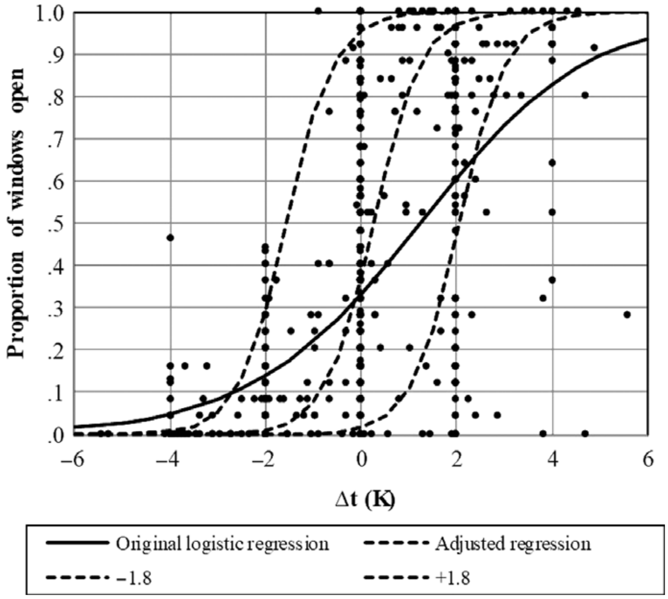

Figure 13. Logistic regression curves of windows open as a function of Δt in all FR modes.[33] The three lines (left: closure from the open position, center, and right: closed to open position) represent the deadband of windows open. Each data point is the mean of 25 sets of raw data observations at the given temperature.

Table 6. 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 25 samples

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	0.427
Variance of logit: var(logit)	2.873
Covariance of Δt and logit: cov(Δt, logit)	1.227
Number of observations in each group: n	25
Proportion of windows open: p	0-1
Mean variance of logit error: var(logit error)	0.3934
Mean logit: logit_m	−0.6937
Mean temperature: Δt_m	−0.1
Residual of Δt	1.20
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=0.495logit+c
Therefore, the equation for logit	logit=2.020Δt+c
The equation must pass through the Δt_m and the logit_m	c=$\text{logit}_m - 2.020\Delta t_m$
The centerline of the deadband	logit=2.020Δt−0.5
The width of deadband	±1.5SD×Residual of Δt
The equations for deadband margins	logit=2.020(Δt±1.8)−0.5
The proportion of windows open	$p=e^{(\text{logit})}/\{1+e^{(\text{logit})}\}$

Table 7. Constraints for each dwelling

	Constrain (K)	
Dwelling	Closed	Open
D1	0.4	**3.2**
D2	0.5	**3.1**
D3	1.2	**2.4**
D4	**3.3**	0.3
D5	1.0	**2.6**
D6	0.9	**2.7**
D7	1.3	**2.3**
D8	0.7	**2.9**
D9	1.3	**2.3**
D10	0.2	**3.4**
D11	1.5	**2.1**
D12	0.4	**3.2**
D13	0.2	**3.4**
D14	0.7	**2.9**
D15	0.6	**3.0**
D16	**2.1**	1.5
D17	**3.1**	0.5
D18	**2.6**	1.0
D19	**1.9**	1.7
D20	0.1	**3.5**
D21	**2.2**	1.4
D22	**3.8**	−0.2
D23	**2.2**	1.4
D24	**2.9**	0.7
D25	**2.5**	1.1
D26	1.2	**2.4**
D27	**2.7**	0.9
D28	0.0	**3.6**
D29	**1.9**	1.7
D30	1.4	**2.2**
D31	1.6	**2.0**
D32	**1.9**	1.7
D33	1.6	**2.0**
D34	**3.3**	0.3
D35	1.7	**1.9**
D36	1.1	**2.5**
D37	**2.5**	1.1
D38	1.0	**2.6**
D39	1.1	**2.5**
D40	**2.3**	1.3
D41	1.4	**2.2**
D42	1.5	**2.1**
D43	1.2	**2.4**
D44	−1.5	**5.1**
D45	0.6	**3.0**
D46	**2.0**	1.6
D47	1.6	**2.0**
D48	1.8	1.8
D49	1.7	**1.9**
D50	**2.0**	1.6
D51	**3.2**	0.4
D52	1.0	**2.6**
D53	1.8	1.8
D54	0.2	**3.4**
D55	1.3	**2.3**
D56	**2.0**	1.6
D57	**3.6**	0.0
D58	1.5	**2.1**

Table 7 (Continued)

Dwelling	Constrain (K)	
	Closed	Open
D59	0.8	**2.8**
Max.	3.8	5.1
Mean	1.5	2.1

Bold: those whose absolute value exceeded 1.8 K.

4. Conclusions

We have explored thermal comfort and window opening behavior in relation to the thermal environment using data from a 4-year study in the living rooms and bedrooms of dwellings in the Kanto region of Japan. We have found the following:

1. Window opening was extremely rare either when the heating was in use or when cooling was turned on.
2. When neither heating nor cooling was in use (the free-running mode), window opening was related both to the indoor temperature and to the outdoor air temperature but occupants of a majority of dwellings tended to have their windows either open or closed for most of the time.
3. The window opening behavior can be predicted from the temperature using logistic regression analysis. The predicted window opening matched well the measured values.
4. The deadband of window opening in these dwellings is 1.8 K, which is smaller than that for European and Pakistani office buildings.
5. The constraint of the window opening in dwellings is smaller than those in the office buildings.
6. The mean indoor comfort temperature was related linearly to the exponentially weighted running mean outdoor temperature in a manner consistent with findings from recent data.

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Disclosure

The authors have no conflict of interest to declare.

Note

Note 1) The outdoor temperature is used for the prediction of the probability of the window being open in the context of thermal modeling. From the point of view of adaptive thermal comfort, the indoor temperature is more fundamental, because it motivates the occupant to open or close the window.

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