Proceedings of 8th Windsor Conference: ***Counting the Cost of Comfort in a changing world***
Cumberland Lodge, Windsor, UK, 10-13 April 2014. London: Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Comfort temperature and the adaptive use of environmental controls in offices in Japan

Ryozo Ooka[1], Madhavi Indraganti[2] and Hom B Rijal[3]

[1] Department of Human and Social Systems, Institute of Industrial Science
4-6-1, Komaba, Meguro-ku, The University of Tokyo, Tokyo 153-8505, Japan
[2] Fulbright- Nehru Post-doctoral Researcher
Center for the Built Environment, University of California, Berkeley
390 Wurster Hall, Berkeley, USA
[3] Department of Restoration Ecology & Built Environment, Tokyo City University, Yokohama, Japan
[1]ooka@iis.u-tokyo.ac.jp
[2]main@berkeley.edu , maindraganti@gmail.com
[3]rijal@tcu.ac.jp

Abstract
Japan's energy perspective underwent a paradigm shift after the 2011 earthquake. It put in place the '*setsuden*' (energy saving) campaign. This recommended minimum and maximum temperature settings for summer and winter, without enough empirical evidence. Many large offices adhered to these, often running them in naturally ventilated (NV) mode. In this context, we surveyed four buildings in Tokyo in summer 2012. About 435 participants provided 2042 sets of data. It contained thermal responses, simultaneous environmental recordings and observations on the use of controls. This paper discusses the comfort temperature and focuses on the occupant behaviour. We found the comfort temperature to be 27.0 °C and 27.4 °C in NV and air-conditioned (AC) modes respectively. Occupants adaptively operated the windows, doors and fans. Logistic regression predicted 80% fan usage at 28 °C of indoor temperature. Offices in AC mode had higher CO_2 level. Many design, operational and behavioural factors hindered adaptive control operation.

Keywords: Thermal comfort; Japan; Occupant behaviour; Adaptive model; Window opening

1 Introduction
The Great Eastern Earthquake and the Tsunami in 2011 have not only caused havoc in Japan, but also rattled the energy conscience of the nation and the world at large. Thereafter, Japan's energy perspective underwent a paradigm shift. Nuclear energy fulfils about 8% of Japan's energy needs (EIA, 2013). With many nuclear plants being shut down after the Fukushima nuclear disaster, Japan faced nation-wide power shortages. These had serious economic consequences for a highly industrialised nation, calling for enormous energy savings. As a fallout, Japan implemented an unprecedented '*setsuden*' (energy saving) campaign in May 2011.

1.1 The *setsuden* campaign
Under this, large consumers were mandated to reduce the peak-power consumption by 15%, while smaller consumers were asked to adhere to 15% reduction in 201. These mandates were translated into two '*minimum and maximum thermostat settings of 28 °C in summer and*

20 °C in winter' respectively. Unfortunately, these dictates seem to be arbitrary and are not supported by solid empirical evidence.

The *setsuden* efforts in the summer 2011 yielded 18% power savings in Tokyo (Ministry of Economy, Trade, and Industry, Japan, 2011). Tanabe et al. discussed in detail, the occupant comfort satisfaction and productivity in offices operating under the *setsuden* conditions in 2011 (Tanabe, et al., 2013).

From a mandatory level, the *setsuden* norms have been changed to a recommendatory level in 2012. Thus, most large scale establishments continued to stick to these, albeit in a relaxed manner. It resulted in offices voluntarily switching off air-conditioning (AC) systems for certain hours and running the offices in naturally ventilated mode (NV) in summer. A field study conducted in summer 2012 clarified on the thermal comfort under the changed scenario in offices (Indraganti, et al., 2013).

Running offices satisfactorily at higher than regular indoor temperatures implies occupant's adaptation through the use of various environmental controls. However, current literature has very little on the occupant adaptation in offices in Japan, while Rijal et al focussed on the user behaviour and adaptation in residential environments (Rijal, et al., 2013).

Interestingly, the studies conducted during 2003 – 2005, i.e., prior to the Fukushima crisis observed no influence of the adaptive opportunity on the thermal perceptions across buildings (Goto, et al., 2007). Therefore, this paper aims to highlight the user behaviour in using various adaptive controls in offices in Japan. It also briefly explains the comfort temperature as noted through a field study in Tokyo, Japan in 2012 summer.

2 Methods

Tokyo lies on humid subtropical climate zone. We conducted a thermal comfort field survey in 88 office spaces in four office buildings of The Tokyo University, in Tokyo during the months of July – September in 2012. The survey was scheduled to include the months of highest discomfort.

Figure 1**.** Typical survey environments, measurement setup and typical female clothing ensembles; (A) Omni-directional probe anemometer (Kanomax Climomaster 6531), (B) Thermo-hygro-CO_2 meter (TR-76Ui), (C) Globe thermometer (TR-52i)

Large play fields and landscaped areas surrounded the surveyed buildings. These are 20 - 30 years old concrete framed structures in two to nine floors. While the lower three floors have concrete in-fill panelled walls, the upper floors have wood and aluminium panelled walls. Most of the spaces have sash or vertically pivoted or sliding windows. Some spaces have balconies with doors too. In most cases the doors opened into the naturally ventilated corridors. All of these buildings were probably designed to operate as AC buildings throughout their service life. Therefore, majority of the windows or doors were not possibly fitted with any shading or rain protection devices. Most of them have operable windows.

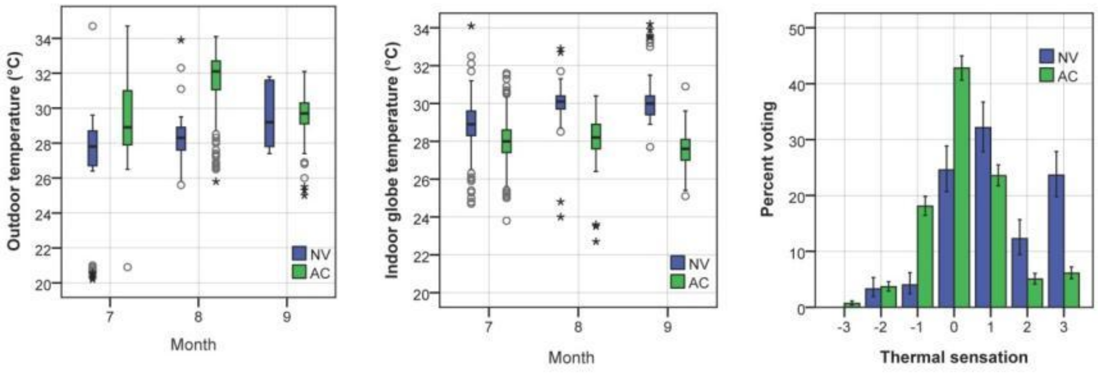
This is a paper based survey. Each of the office was visited twice or thrice a day, leaving a minimum gap of two hours in between. The second author interviewed all the 435 voluntary participants. She gathered 2402 sets of data. This data consisted of thermal responses, simultaneous recordings of environmental measurements and her observations about the subject's clothing, activity and use of various environmental controls. The controls observed were: windows, doors, common and personal fans, general and personal table lights and AC systems. Venetian blinds and rolling screens or traditional bamboo screens are fitted to all the windows and balcony doors.

We used calibrated high-precision digital instruments following the American Society of Heating Refrigeration and Air-conditioning Engineers (ASHRAE)'s Class-II protocols for field survey (ASHRAE, 2010). The typical survey environments, instrument set-up and the clothing ensembles used by women subjects are presented in Fig. 1.

The subject sample included 290 males. They are in the age group of 20 – 70 years. Men provided 51.2% of the data. About 22.1% the subjects were non-Japanese occupants. We estimated the clothing insulation of the subjects' ensembles using the summation method and standard lists (ASHRAE, 2010). Most of the subjects followed the '*coolbiz*' suggestions and were in light summer clothing (mean clo = 0.63 clo, SD = 0.08). We did not observe any significant gender or modal differences in the total clothing insulation. A detailed account on the methods and the subject sample is in Indraganti et al. (Indraganti, et al., 2013).

3 Results and Discussion

3.1 Thermal conditions and comfort responses



A B C

Figure 2. Box-plots of outdoor and indoor globe temperatures and thermal sensation in NV and AC modes

Outdoor temperature during the three months of survey varied from 20.2 °C to 34.7 °C, with 29.7 °C as mean (standard deviation (SD) = 2.49 K). Outdoor humidity remained quite high throughout the survey averaging at 63.5% and ranged from 41% to 93%. The survey lasted from July 4 to September 11. Warm-humid summer conditions with intense discomfort prevailed throughout the survey.

Indoor conditions and temporal variations

Due to the *setsuden* requirements most of the offices operated their AC systems adaptively, probably when it was hot outside. They functioned in NV mode rest of the time (usually in the morning and in the evening). Our study included both these modes of operation. The survey continued from morning till late in the evening on all the survey days. Each of the comfort response and the simultaneous recording of the temperature are noted against the voting time. All the voting times are ranked and divided into ten equal interval groups of approximately equal sample size (deciles) using the statistical package SPSS ver. 20. Figure 3 shows the temporal variation in indoor globe temperature observed during the three months of survey. It shows on the x-axis mean voting time of the decile group, and the mean indoor globe temperature at that time as observed in the field. It can be seen that temperature in NV mode fluctuated more during the day.

Indoor globe temperature (T_g) was less variable compared to the outdoor temperature (Figure 2B). Hygro-thermal conditions in NV mode were more variable than in AC mode. In NV mode, mean T_g was 29.4 °C (N = 423, SD = 1.5 K) and in AC mode it was slightly lower averaging at 27.9 °C (N = 1979, SD = 1.2 K). Similarly, the mean indoor relative humidity was 52.6 % (SD = 6.4%) and 50.9 % (SD = 4.4%) in NV and AC modes respectively. Air velocity in AC mode was slightly higher than NV. The median of air velocity in AC mode was 0.21 m/s while it was 0.18 m/s in NV mode.

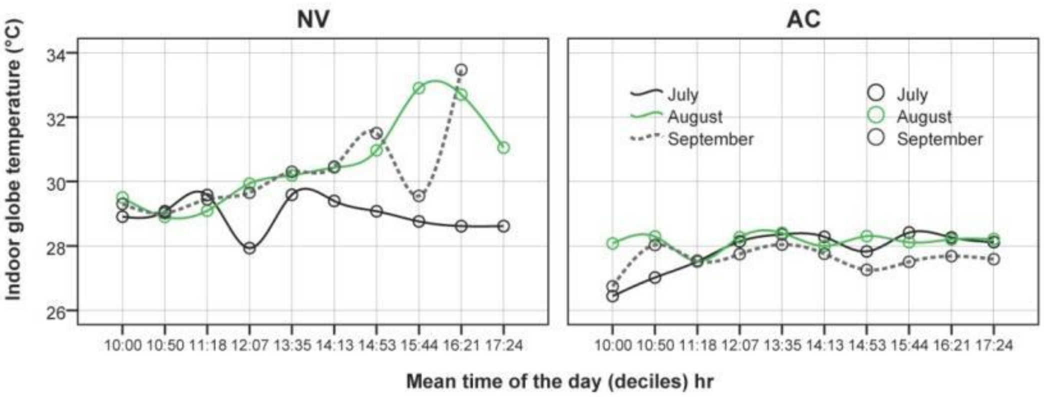


Figure 3. Temporal variation in the indoor globe temperature during the three months of survey

Thermal sensation (TS)

We measured the thermal sensation on ASHRAE's seven point scale. A significantly higher percentage of people voted on the warmer side of the scale in the NV mode than in AC mode at 95% confidence interval (CI) (Fig. 2C). In NV mode only 69.1 % were comfortable (voting between -1 to +1) and in AC mode 84.4 %. About 31.9% and 65.3% felt 'neutral' sensation in NV and AC modes respectively. Mean sensation in NV mode was 1.17 (SD = 1.3) and AC mode was 0.24 (SD = 1.2).

In a 2011 summer (July through August) study in Tokyo offices, Tanabe et al. noted greater variability in the mean sensation vote. They found it varying between -0.7 (SD = 1.1) to 2.0 (SD = 1.3). They noted the mean indoor air temperature varying between 25.3 °C (SD = 0.3 K) and 29 °C (SD = 0.9 K), while the relative humidity varied between 46 – 60% (Tanabe, et al., 2013).

Comfort temperature (T_{comf})

We estimated the comfort temperature (T_{comf}) by Griffiths' method using 0.5 as the Griffith's coefficient (G) using the following relationship (Griffiths, 1990):

$$\mathbf{T_{comf} = T_g + (0 - TS) / G} \quad \ldots\ldots(1)$$

Figure 4 shows the distribution of the comfort temperature. Mean comfort temperature was found to be 27.0 °C in NV mode and about half a degree higher in AC mode (27.4 °C). Temperature and humidity in NV environments are significantly higher than those of AC mode. Absolute humidity is 13.4 g/kg.da and 11.9 g/kg.da in NV and AC modes respectively. Occupants in AC mode also have achieved higher air movement by using fans. This in part explains the higher comfort temperature in AC mode as observed here.

The running mean of the outdoor temperature better explains the effects of outdoor conditions on the indoors (Humphreys, et al., 2013). The running mean of the outdoor mean temperature was estimated for all the data sets using the relationship,

$$\mathbf{T_{rm\ (tomorrow)} = (\alpha)\ T_{rm\ (yesterday)} + (1\text{-}\alpha)\ T_{m\ (today)}} \quad \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Where, T_{rm} is the running mean temperature (°C), T_m is the outdoor daily mean temperature (°C), and α is a unit less constant between 0 and 1 and is usually taken as 0.8. It indicates a half-life of approximately 3.5 days (Humphreys, et al., 2013).

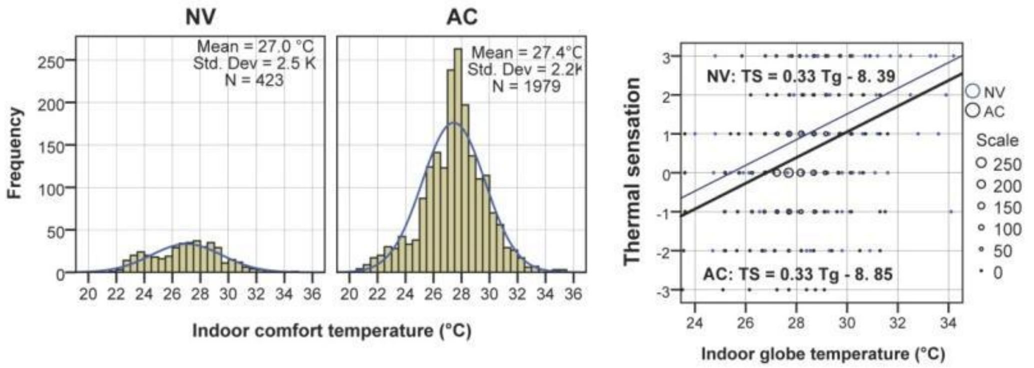


Figure 4. Comfort temperature distribution in NV and AC modes and regression of indoor globe temperature with the thermal sensation ($p < 0.001$)

The occupant's thermal sensation varied with the indoor globe temperature. However, the slope of the equation for NV mode was not significantly different from the AC mode, although both the relationships were themselves significant. Hence, we used the general linear regression model which assumes equal slope for both the categories (NV and AC) using 'mode' as the fixed variable, and obtained the following relationships ($p<0.001$):

NV Mode: $\mathbf{TS = 0.33\ T_g - 8.39}$ ……………(3)

AC Mode: $\mathbf{TS = 0.33\ T_g - 8.85}$ ……………(4)

Using these equations, the neutral temperature (coinciding with '0' on the sensation scale) was found to be 25.4 °C and 26.8 °C in NV and AC modes respectively.

3.2 The Adaptive model

NV mode

An adaptive relationship was noted between indoor and outdoor temperatures as shown in the Figure 5A. It shows the variation in monthly mean indoor globe temperature (T_{gmm}) with monthly mean outdoor temperature (T_{omm}) for both NV and AC modes. The gradient of the relationship (slope = 0.35 K^{-1}) for NV mode matched very closely with the slope of the ASHRAE's adaptive model (slope = 0.31 K^{-1}) (de Dear & Brager, 1998). The comfort temperature and outdoor mean temperature relationship as observed in Japan by Goto et al. was also above the ASHRAE's adaptive model (Goto, et al., 2007).

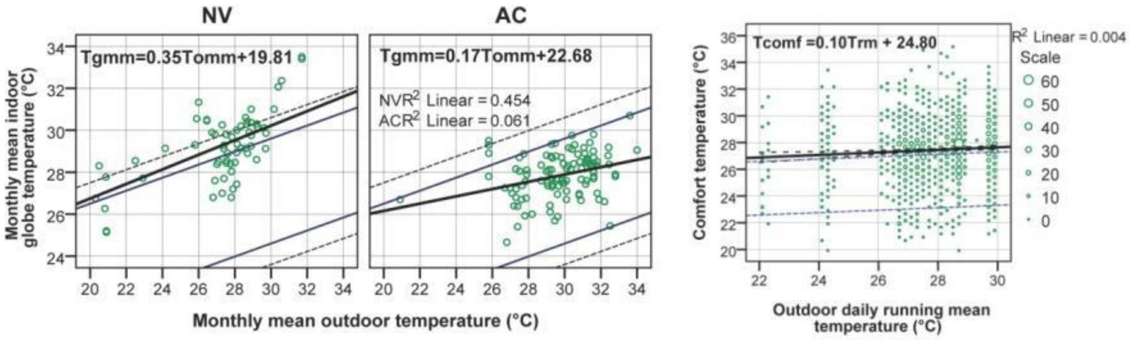
European standards (CEN:15251, 2007) mention a similar relationship, where the slope of the equation between outdoor daily running mean temperature and indoor comfort temperature is 0.33 K^{-1}. It appears that the subjects' comfort responses in European and Japanese offices are very similar to one another.

AC mode

In AC mode, we observed the indoor comfort temperature changing significantly with the outdoor daily running mean temperature as shown in Figure 5B. The following equation was obtained:

$$\mathbf{T_{comf} = 0.10\ T_{rm} + 24.80} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

(N = 1979, r = 0.30, S.E. = 0.032, p=0.003)



A B

Figure 5. (A) An adaptive relationship between T_{omm} and T_{gmm} for NV and AC modes (p<0.001); Also shown superimposed are the 90% and 80% limits of the ASHRAE's adaptive model; Each point represents the aggregated monthly data for an office; (B) A similar relationship between T_{rm} and T_{comf} (p<0.01), superimposed with the upper and lower limits of a similar model from the CIBSE guide; Dotted lines indicate 95% CI of slope; Each point is a single dataset.

Nevertheless, we could not find a significant relationship in NV mode. As the quantity of data was very limited, we could not get a meaningful significance. Figure 5B shows the relationship from the CIBSE guide, which is based on the surveys in European offices (CIBSE, (The Chartered Institution of Building Services Engineers, 2006; Nicol & Humphreys, 2007).

Interestingly the slope of the regression line from this study (0.1 K^{-1}) matched very closely with the slope of the line from the European data (0.09 K^{-1}). It is also comparable to the slope of the equation (0.15 K^{-1}) obtained in Indian offices in AC mode (Indraganti, et al., 2014). A large scale residential building study in Japan reported a slope of 0.297 K^{-1} in AC mode (Rijal, et al., 2013). It points to a very high variability in comfort temperature in homes, for a step change in outdoor temperature, also indicating high occupant adaptation in residential spaces.

However, both the regression lines in NV and AC modes lie very close to the upper limits of the ASHRAE's adaptive model and CIBSE's model respectively, while the slopes matched very closely (Figure 5A, B). This indicates occupant adaptation at higher indoor temperatures, generally observed in Japanese offices. The following sections explain this.

3.3 Occupants' adaptive behaviour

We noted various environmental controls put to use in this summer study. The controls observed were windows, doors, blinds, fans and hand fans. Occupants used many kinds of fans: floor mounted high power fans, floor mounted and table mounted tower fans, small table fans, very small USB (universal serial bus) fans and hand fans.

During the field survey we recorded the use of a fan as binary data (0 = not in use; 1= in use). They are noted down as general fans and personal fans. In this study the use of fan includes both personal and general fans. Similar to the fans, windows, doors and blinds are noted down as binary data (0 = closed, 1 = open). Table 1 shows the mean proportion of use of controls in NV and AC modes as observed in various offices.

When the indoor temperature exceeds the comfort temperature occupants make use of the environmental controls to restore thermal comfort. Many researchers found empirical evidence for this (Brager, et al., 2004; Rijal, et al., 2008; Rijal, et al., 2007). Temperature seems to be key stimulus to the operation of controls. Greater use of controls is expected at higher temperature.

Table 1: Mean proportion of use of controls

Mode	Building	N	Windows open	Doors open	N	Fans on
NV	AS	4	0.50	1.00	4	0.25
	IIS	419	0.84	0.78	316	0.67
All NV		423	0.83	0.78	320	0.66
AC	AS	27	0.19	0.00	27	0.15
	IIS	1790	0.00	0.01	1500	0.78
	K1	160	0.04	0.00	160	0.96
	KL	2	0.00	0.00	2	0.00
All AC		1979	0.01	0.01	1689	0.79

N = Number of observations

While all the surveyed offices have windows and doors, some of the spaces surveyed do not have fans. Table 1 presents the proportion of use of controls in each of the surveyed building in both NV and AC modes. As can be observed, we found the windows open in 83% of the cases and 78% doors open in NV mode. The use of windows and doors was very limited in AC mode. Therefore, these two controls are analysed in NV mode while the use of fans is examined in both the modes.

Table 2: Changes in indoor environmental variables with the use of windows and doors (NV mode)

Environmental variable	Windows closed		Windows open	
	Door closed	Door open	Door closed	Door open
Sample size	29	39	63	290
Outdoor air temperature (°C)	28.0	26.6	28.8	27.3
Comfort temperature (°C)	27.2	25.8	28.0	26.9
Indoor air temperature (°C)	28.9	29.1	30.2	29.2
Indoor globe temperature (°C)	28.9	28.9	30.1	29.3
Air velocity (m/s)	0.24	0.18	0.14	0.21
Relative humidity (%)	50.7	59.5	49.9	52.5
Humidity ratio (g/kgda)	12.5	15.1	13.3	13.2
CO2 level (ppm)	889	610	643	577
Fan usage (%)	0.76	0.69	0.67	0.65

The data are ranked and binned into quartiles of indoor and outdoor temperatures, containing roughly equal number of samples. Figure 6 shows the proportion of open windows, open doors, open blinds and 'fans on' in NV mode in each of the temperature bins with 95% CI. The proportion of open windows, open blinds and fans in use increased with temperature. The proportion of '*doors open*' remains quite high throughout at around 83%, where as the window usage varied from 77% to 90%.

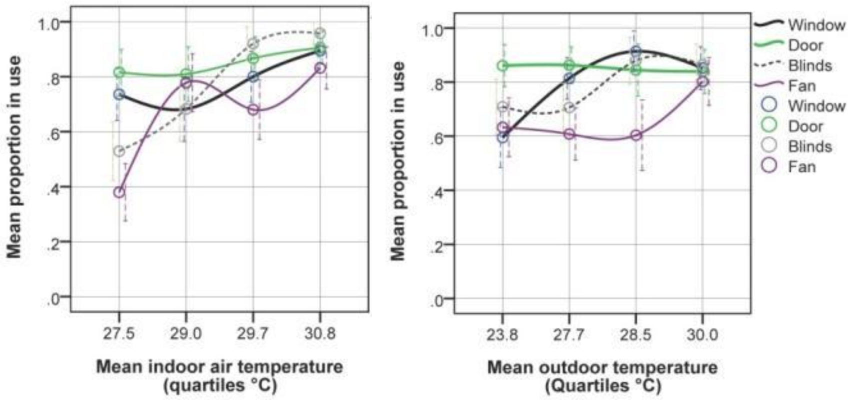


Figure 6. Proportion of windows open, doors open, blinds open and fans on with 95% CI at quartiles of indoor air temperature and outdoor mean temperature

Order of priority between the use of controls

We noted a complex inter-relationship/ dependency among the use of controls. It is generally believed and there is some field study evidence from Pakistan, that occupants open the windows and doors as a first reaction (Rijal, et al., 2008). We found this hypothesis applying to our data as well. For example, a closer look at Figure 6 reveals that at lower outdoor or indoor temperatures, the proportion of usage is lowest for fans, medium for windows and highest for doors.

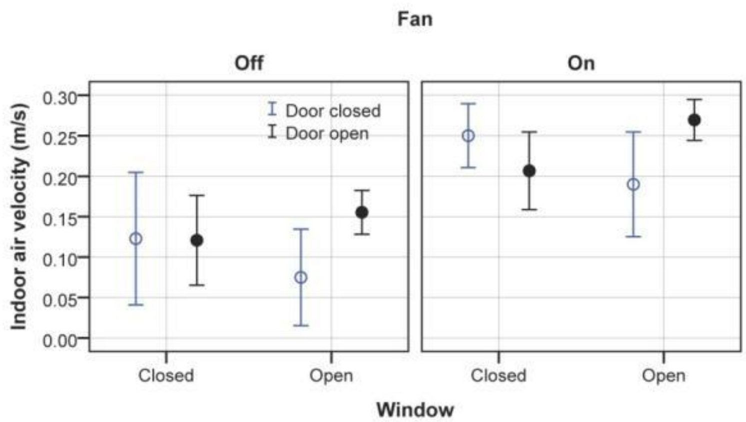


Figure 7. Indoor air velocity when windows, doors and fans are in use with 95% CI in NV mode

Use of windows and doors has also impacted the indoor environment as shown in Table 2 and Table 3. In general, we noticed doors and windows being open in conditions where indoor temperatures and humidity were high. Moreover, the occupants perhaps preferred to close the windows and doors when the outdoor temperature is very high and use of the fans is more. This is indicated by higher proportion of '*fans on*', when both windows and doors were closed.

In addition, perhaps as the fans were used more, the subjects successfully achieved higher mean indoor airspeeds even when the doors and windows were closed, than when they both were open (Figure 7). As a result, the mean indoor comfort temperature is also slightly higher with both doors and windows closed than otherwise. It is to be noted that this difference is not statistically significant at 95% CI.

The combined effect of windows, doors and fans on indoor air speeds is profound. Operation of controls increased the mean air movement to about 0.27 m/s. Figure 7 shows the air speeds when the three controls are operated in NV mode with 95% CI. Significantly higher indoor air speeds are noted when fans were 'on' and windows and doors were open, than otherwise.

It also important to note that use of doors and windows posed many operational and spatial constraints.

As a result, a mere thermal stimulus perhaps was not sufficient for their complete operation. These constraints would be discussed subsequently. As can be seen in the Table 3, window usage correlated rather poorly with the temperature. On the other hand, door usage correlated negatively with the temperature. It is likely that people preferred to close the doors at high temperatures, and used fans and windows to provide for the necessary air movement. Fan usage showed a much stronger positive correlation in both the modes with temperature.

Table 3: Correlations of usage of controls with indoor and outdoor environmental variables

Mode	Control	N	T_m : control	T_o : control	T_a : control	T_g : control	V_a : control
NV	Window	423	-0.02	0.06	0.08	0.13**	-0.01
NV	Door	423	-0.23**	-0.19**	-0.18**	-0.11*	0.10*
NV	Fan	320	0.37**	0.27**	0.27**	0.23**	0.36**
AC	Fan	1689	0.12**	0.07**	0.12**	0.09**	0.29**

**. Correlation is significant at the 0.01 level (2-tailed); *. Correlation is significant at the 0.05 level (2-tailed). T_m: Outdoor daily mean temperature (°C); T_o: outdoor temperature (°C); T_a: indoor air temperature (°C); T_g: indoor globe temperature (°C); indoor air velocity (m/s)

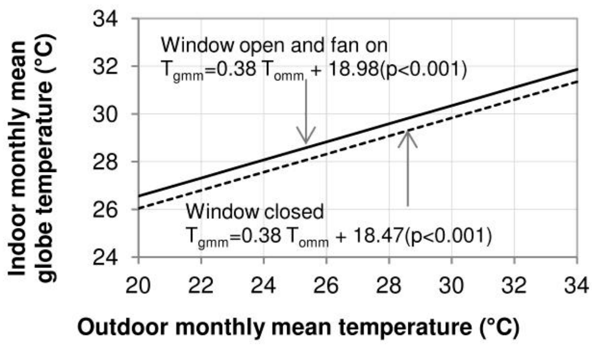


Figure 8. Relationship between indoor and outdoor temperatures with windows open and fan on and windows closed ($p<0.001$)

Open windows and fans in use had a positive effect on the indoor temperature in NV mode by improving thermal comfort and the fans in use had a similar effect in AC mode. Figure 8 shows the regression between outdoor temperature and indoor globe temperature aggregated over a month for each of the offices in NV mode. The two lines are the general linear regression lines indicating equal slope, and varying y-intercepts caused by the use of fan and window. The difference is statistically significant at $p<0.001$. It means that the subjects had a higher indoor mean temperature when using open windows and fans than when they both were not in use.

Algorithm to predict the use of fans

The contribution of fans to improve the indoor air velocity and thereby comfort at warm temperatures is well known (Rijal, et al., 2008; Rijal, et al., 2007; Rijal, et al., 2013; Indraganti, et al., 2014). Algorithms to predict the fan usage are useful in simulation studies.

Nicol mentions that a stochastic relationship better explains the association between fan usage and the indoor/ outdoor temperature (Nicol, 2001). For example, the probability of fan being in use (P_f) against an external stimulus such as indoor/ outdoor air temperature (T_a) can be examined. Logistic regression is widely used for this (Haldi & Robinson, 2008; Rijal, et al., 2008; Rijal, et al., 2013; Indraganti, et al., 2014; Yun & Steemers, 2008).

The logit is given by the equation:

$$\text{Logit}\ (p) = \log\ (p/(1\text{-}p)) = \text{b}T+c \quad \text{...}(6)$$

Where,

$$p = e^{(bT+c)} / (1+e^{(bT+c)}) \quad \text{...}(7)$$

Where p is the probability that the fan being on, T is the temperature (in this case indoor air temperature), b is the regression coefficient for T, and c is the constant in the regression equation.

The logistic regression of P_f and indoor air temperature (T_a) yielded the following equations with the following standard error of slope (SE) and Negelkerke R^2 values:

NV mode: **logit (p) = 0.441 T_a – 12.18** ……………………………………….(8)

(N= 320; R^2 = 0.101; SE = 0.096, $p<0.001$)

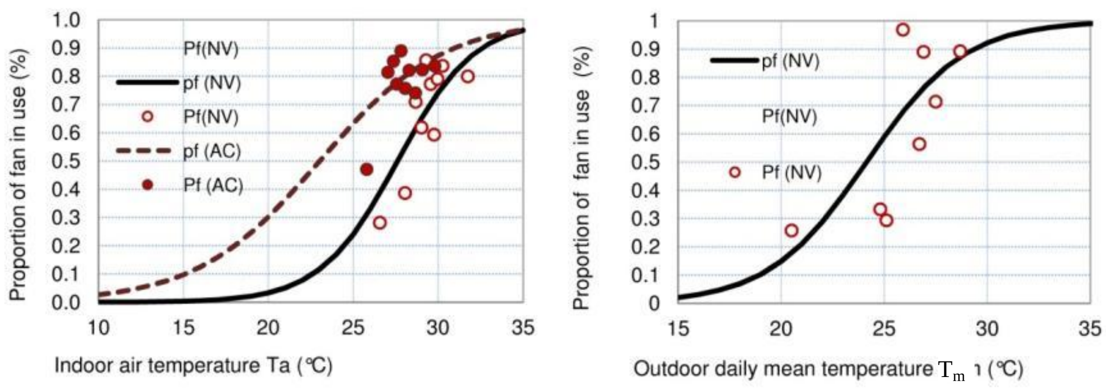
AC mode: **logit (p) = 0.277 T_a – 6.38** ……………………………………….(9)

(N= 1689; R^2 = 0.021; SE = 0.058, $p<0.001$)

Similarly, the logistic regression of P_f and outdoor daily mean temperature (T_m) yielded the following equation with the following standard error of slope (SE) and Negelkerke R^2 values:

NV mode: **logit (p) = 0.422 T_m – 10.19** ……………………………………….(10)

(N= 423; R^2 = 0.179; SE = 0.073, $p<0.001$)



A B

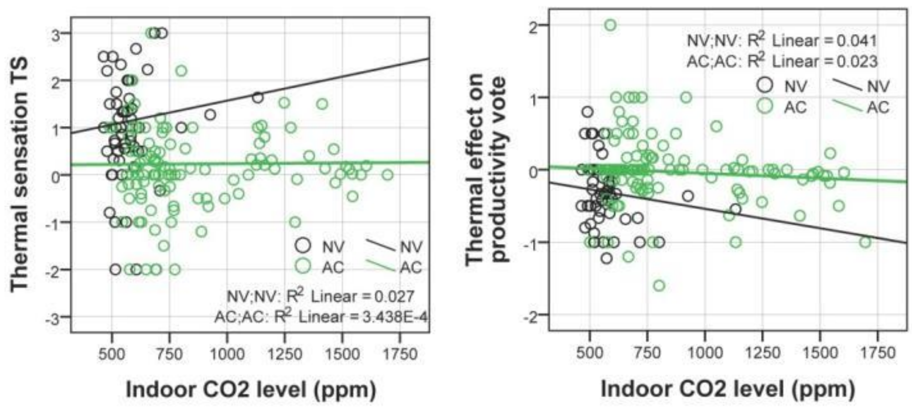
Figure 9. Logistic regression of proportion of fans in use with (A) indoor air temperature (B) outdoor daily mean temperature with actual data superimposed for both NV and AC modes ($p<0.001$). Each point is from aggregated from ranked deciles of temperature.

These equations (8) and (9) are shown in Figure 9A and equation (10) in Figure 9B, with binned data from the field study superimposed on them. The actual data matches the regression line well. Using this equation we can estimate that at an indoor air temperature of 28 °C, about 80% fans would be running.

These equations matched closely with the findings from other reports. Pakistan survey reported a slope of 0.426 (with Cox and Snell R^2 of 0.48) for the logistic regression of indoor globe temperature and fan usage in NV mode. Their equation also predicted 75% fan usage at 28 °C of globe temperature (Rijal, et al., 2008). An Indian field study in summer obtained a logistic regression coefficient of 0.448 when the fan usage was regressed with indoor globe temperature (Indraganti, et al., 2013). They predicted 80% fans to be in use when the indoor temperature would be at 29 °C.

3.3 Indoor CO_2 level and the thermal effect on productivity

Indoor CO_2 level depended very heavily on the use of openings. It was significantly lower in NV mode when the windows and doors were open than it is in AC mode (at 95% CI). We enquired all the subjects about the thermal effect on their productivity (TPR) on a five point equal interval scale. The scale had '0' in the center indicating '*no effect*'. The scale points +2 and -2 referred to '*much higher than normal*' and '*much lower than normal*' productivity respectively.



A B

Figure 10. Variation in (A) thermal sensation (B) thermal effect on productivity vote with indoor CO2 for both NV and AC modes. Each point represents the aggregated monthly data from an office.

We aggregated the TS, TPR and CO_2 level data for all the offices in all the months for both the modes. We then regressed the mean data. This is shown in Figure 10. It appears that an increase in CO_2 concentration has clearly elevated the thermal sensation vote in NV mode while it had little effect in AC mode. Similarly, at higher CO_2 levels, subjects voted their self declared productivity to be lower than normal in NV mode, while in AC mode the difference is marginal.

Increased CO_2 concentrations usually occurred in NV mode when the doors and windows were closed. This perhaps could have increased the indoor temperatures also, leading a higher sensation vote, causing discomfort in turn. This thermal discomfort also could have affected the occupant's productivity vote. This in part explains higher TS and lower TPR votes at higher CO_2 levels. Tanabe et al also have observed lower satisfaction levels at higher CO_2 levels in a Japan study (Tanabe, et al., 2013).

4 Obstacles in successful operation of controls

We noted many hindrances to the successful operation of environmental controls like windows, doors, blinds and fans. While some of these are related to the design, operation and maintenance factors, others are borne out of occupants' thermal history and other behavioural issues. These are discussed here very briefly.

4.1 Design factors

Majority of the offices surveyed were designed to be run with the help of active systems like air conditioners throughout their service life. Perhaps the design indoor temperatures were much lower than the temperature settings of the *setuden* for summer (28 °C). As a result, a majority of the buildings were not fitted with well designed operable windows or ceiling fans. Most of the windows and balcony doors lacked shading devices (Figure 11).

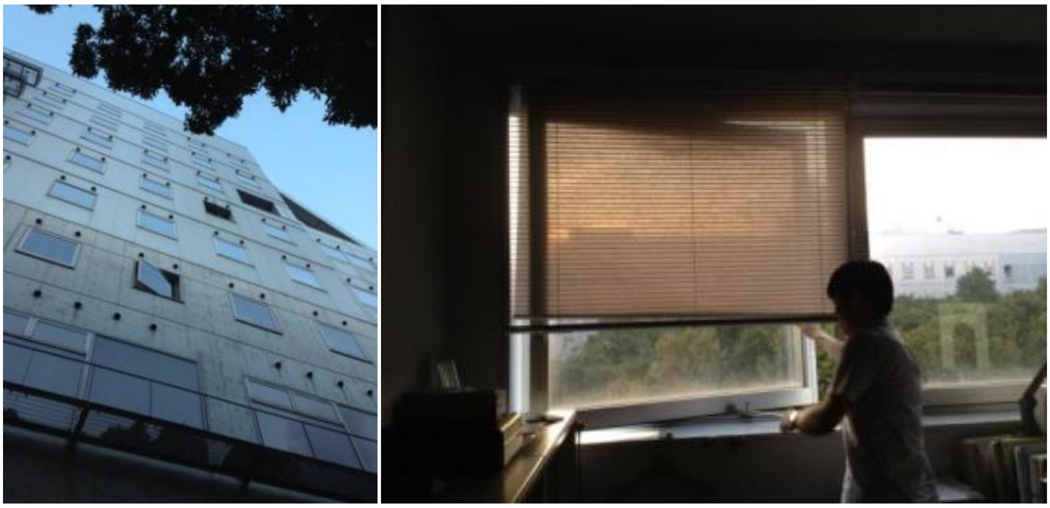


Figure 11. Windows and balcony doors in buildings designed to be run under AC throughout not fitted with sun/ rain protection devices; Operation of the vertically pivoted window interfering with the venetian blind, obstructing simultaneous use of both the controls

Vertical pivoting of windows curtailed wider opening of the window shutter. The shutter could not be turned beyond the window jamb as it interfered with the venetian blinds fitted to the interior wall. Therefore, windows could not be opened fully well. Most of the ventilating corridors were fitted with vertically pivoted windows. These obstructed the user movement in the corridors (Figure 12). In some cases, the bottom hung horizontal high level smoke vents were opened and were used adaptively, in NV mode. However, these could not be used for long during the day, due to occasional rain splashing into the interior.

4.2 Operation and maintenance factors

Figure 12. Opening the ventilating doors into the thoroughfare passage ways directly affected privacy; Vertically pivoted windows in the ventilating corridor obstruct free movement of people.

Most of the work-stations are not provided with personal fans (80 – 86%). Tanabe at al. noted that the plug-in power supply in the year 2011 was seriously restricted in offices due to stringent *setsuden* norms (Tanabe, et al., 2013). In this study we observed floor mounted common fans being used to provide increased air movement at elevated temperatures. About 3 – 6% did not have access to these also. Anecdotal responses revealed that, in the absence of ceiling fans, air movement distribution throughout the serviced area perhaps could not successfully be achieved with these. Thus, non-availability of additional personal fans was found to be a limitation to achieve thermal comfort in summer. As the ventilating doors in a majority of offices opened in to the main thoroughfare corridors, opening them affected privacy, and perhaps also has caused mild disturbance. This in some cases has limited the door usage.

4.3 Thermal history and behavioural factors

Japanese office occupants are possibly accustomed to much lower indoor temperatures prior to the *setsuden* in 2011. Field studies conducted in Japanese offices in the year 2003 to 2007 provide evidence to this. Goto et al. noted the indoor temperatures in the offices to be in range of 22.5 °C (SD = 0.8 K) in the morning while the peak temperature was around 26.9 (SD = 0.8 K) in summer (Goto, et al., 2007). The indoor temperatures recorded in our study are higher than this.

It appears that the subjects had a thermal history of working in overcooled environments in the previous years, without the necessity of using the environmental controls like fans, windows and doors adaptively. This might have inhibited the occupants from fully exploiting the available environmental controls prior to adaptively switching on the AC systems.

The occupants used the AC systems adaptively in summer. They ran the offices in NV mode for three to four hours in the morning and then switched the AC systems on, when the outdoor temperature was high. However, we noticed some subjects having slight attitudinal non-preparedness in switching back to the NV mode during the day. Yun and Steemers observed similar time-dependent occupant behaviour in UK offices in opening and closing the windows (Yun & Steemers, 2008). Ackerly and Brager found the window signalling systems beneficial if their purpose was well understood and that they were visible to the occupant. It may be beneficial to install such systems to encourage longer spells of operation in NV mode (Ackerly & Brager, 2013). They emphasise on effective communication with the occupant.

5 Concluding remarks

In a field study in four offices in Tokyo in summer 2012 we collected the thermal comfort responses and simultaneous environmental measurements. All the offices attempted to observe the *setsuden* recommendation for indoor temperatures during the survey. The adaptive model is proposed and the comfort temperature in summer is found to be 27.0 and 27.4 °C in NV and AC modes respectively. Window operation improved the indoor conditions. Fan usage increased with temperature. Our logistic regression equation predicted that, about 80% fans would be on when the indoor temperature would around 28 °C. Adaptive operation of environmental controls was hindered by design, operation and maintenance factors, which are not in the direct control of the occupant often times. Occupants' thermal history of cooler temperatures in offices perhaps could have hindered the adaptive use of environmental controls. In the changed scenario of energy concerns, it may be prudent to relook at the design of openings and take advantage of increased air movement even in fully air-conditioned buildings in Japan.

Acknowledgements

The Japan Society for Promotion of Science and The University of Tokyo, Japan funded this research. For data analysis, we used the facilities at the Centre for the Built Environment, University of California Berkeley, made available through the Fulbright Grant. They all are thanked for their financial and logistic support. We acknowledge the participation of all the heads of offices and the subjects for their involvement.

References

Ackerly, K. & Brager, G., 2013. Window signalling systems: control strategies and occupant behaviour. *Building Research & Information,* 41(3), pp. 342-360.

ASHRAE, 2010. *ANSI/ ASHRAE Standard 55-2010, Thermal environmental conditions for human occupancy,* Atlanta: s.n.

Brager, G. S., Paliaga, G. & de Dear, R., 2004. Operable Windows, Personal Control. *ASHRAE transaction*, pp. Vol.110, Part 2, pp 17-35.

CEN:15251, 2007. *Indoor environmental input parameters for design and assessment of energy performance of buildings: addressing indoor air quality, thermal environment, lighting and acoustics.*. Brussels: Commite European de Normalisation.

CIBSE, (The Chartered Institution of Building Services Engineers, 2006. *Environmental Design Guide, Vol.A,* London: s.n.

de Dear, R. J. & Brager, G. S., 1998. Developing an Adaptive Model of Thermal Comfort and Preference. *ASHRAE Transactions,* 104(1), p. 145–167 .

EIA, E. I. A., 2013. *Country analysis briefs, Japan,,* s.l.: s.n.

Goto, T. et al., 2007. Long-term field survey on thermal adaptation in office buildings in Japan. *Building and Environment,* Volume 42, pp. 3944-54.

Griffiths, I. D., 1990. *Thermal Comfort in Buildings with Passive Solar Features: Field Studies ,* s.l.: s.n.

Haldi, F. & Robinson, D., 2008. On the behaviour and adaptation of office occupants. *Building and Environment,* Volume 43, pp. 2163-2177.

Humphreys, M., Rijal, H. & Nicol, J., 2013. Updating the adaptive relation between climate and comfort indoors; new insights and an extended database. *Building and Environment ,* Volume 63, pp. 40-45.

Indraganti, M., Ooka, R. & Rijal, H. B., 2013. Field investigation of comfort temperature in Indian office buildings: a case of Chennai and Hyderabad. *Building and Environment,* 65(7), pp. 195-214.

Indraganti, M., Ooka, R. & Rijal, H. B., 2013. Thermal comfort in offices in summer: Findings from a field study under the 'setsuden' conditions in Tokyo, Japan. *Building and Environment,* 61(3), pp. 114-132.

Indraganti, M., Ooka, R., Rijal, H. B. & Brager, G. S., 2014. Adaptive model of thermal comfort for offices in hot and humid climates of India. *Building and Environment,* p. 10.1016/j.buildenv.2014.01.002.

Ministry of Economy, Trade, and Industry, Japan, 2011. *Summary of setsuden during summer of 2011,* s.l.: s.n.

Nicol, F. & Humphreys, M., 2007. Maximum temperatures in European office buildings to avoid heat discomfort. *Solar Energy,* Volume 81, pp. 295-304.

Nicol, F. J., 2001. *Characterising occupant behaviour in buildings: towards a stochastic model of occupant use of windows, lights, blinds, heaters and fans.* Rio, Brazil, Proceedings of the seventh international IBPSA conference.

Rijal, H. B., Honjo, M., Kobayashi, R. & Nakaya, T., 2013. Investigation of comfort temperature, adaptive model and the window-opening behaviour in Japanese houses. *Architectural Science Review,* 56(1), pp. 54-69.

Rijal, H. B. et al., 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,* SL-08(056), pp. 555-573.

Rijal, H. B. et al., 2007. Using results from field surveys to predict the effect of open windows on thermal comfort and energy use in buildings. *Energy and Buildings,* p. 39 (2007) 823–836 .

Rijal, H. B. et al., 2008. Development of an adaptive window opening algorithm to predict the thermal comfort, energy use and overheating in buildings. *Journal of Builing Performance Simulation,* pp. Vol 1, No1, March 2008, 17-30 .

Tanabe, S.-i., Iwahashi, Y., Tsushima, S. & Nishihara, N., 2013. Thermal comfort and productivity in offices under mandatory electricity savings after the Great East Japan earthquake. *Architectural Science Review,* 56(1), pp. 4-13.

Yun, G. Y. & Steemers, K., 2008. Time-dependent occupant behaviour models of window control in summer. *Building and Environment,* 43(9), pp. 1471- 1482.