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# Behavioural Adaptation for the Thermal Comfort and Energy Saving in Japanese Offices

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**Abstract:** Office workers use a variety of adaptive opportunities to regulate their indoor thermal environment. The behavioural adaptations such as window opening, clothing adjustments, and use of heating/cooling are important factors for adaptive thermal comfort. It is well-known that they are the most important contributors in the adaptive thermal comfort model. Thus, if we understand the behavioural adaptation properly, we can explain the mechanism of the adaptive model. The indoor thermal environment is often adjusted using the air conditioning in Japanese office buildings to improve thermal comfort and productivity. Thus, it is necessary to conduct research on the behavioural adaptation in the offices because the occupant behavior is different from behaviour in dwellings. In order to record the seasonal differences in behavioural adaptation and to develop an adaptive algorithm for Japanese offices, we measured temperatures in 11 office buildings and conducted the thermal comfort and occupant behaviour survey for over a year. We collected 4,660 samples from about 1,350 people. The proportion of 'open window' in the free running mode (neither heating nor cooling being used) is significantly higher than that of the air conditioned mode. The behavioural adaptation is related to the outdoor air temperature. The behavioural adaptations such as window-opening, heating and cooling use predicted by regression analysis are in good agreement with the measured data. These findings can be applied to building thermal simulation to predict the behavioural adaptation and energy use in office buildings.

**Keywords:** Office buildings, Thermal comfort, Occupant behaviour, Window opening, Clothing adjustment, Heating and cooling use.

## 1. Introduction

People use a variety of adaptive opportunities to regulate their indoor thermal environment. The behavioural adaptations such as window opening, clothing adjustments, fan/heating/cooling use are some of the important factors for adaptive thermal comfort. It is well-known that they are the most important contributors in the adaptive thermal comfort model. Thus, if we understand the behavioural adaptation properly, we can explain the much of the mechanism of the adaptive model. In addition, the indoor thermal environment is often adjusted using the air conditioning in the Japanese office building to improve the thermal comfort and productivity. However, temperature control using window opening can reduce environmental impact by reducing the use of air conditioning as much as possible. Thus, it is necessary to conduct research on the behavioural adaptation in the offices because the occupant behavior is different from adaptive behaviour in dwellings.

A number of projects have researched occupant behaviour in offices [2, 5, 9, 13, 21-25, 27, 30], university buildings [28, 29] and dwellings [1, 3, 8, 10, 11, 16-18, 20]. The occupant behaviour model developed for office buildings in other countries [22] may not apply to Japan and research about occupant behaviour is needed for Japanese offices, for results from one region of the world cannot be assumed to apply to another where there is a different culture and building design. Thermal simulation packages often assume a fixed schedule of window opening [23], so more realistic data on occupant behaviour will help to improve the thermal simulations and an adaptive algorithm becomes a useful passive design tool. In order to record the seasonal differences in behavioural adaptation and to develop an adaptive algorithm for Japanese offices, we measured temperatures in 11 office buildings and conducted occupant behaviour survey for over a year in the Tokyo and Yokohama areas of Japan.

## 2. Methodology

### 2.1 Investigated Buildings

In this survey, 11 office buildings were investigated in the Tokyo and Yokohama areas of Japan from August 2014 to October 2015 (see Table 1). These buildings are readily available in the investigated areas. The numbers of HVAC and mixed mode buildings are five and six respectively.

**Table 1:** Description of the investigated buildings [19]

| Building code | Location | Building construction | Mode | HVAC control | Window | Natural ventilation opening | Number of floor* | Investigated floor* | Number of survey months |
|---|---|---|---|---|---|---|---|---|---|
| B1 | Tokyo | S, RC | HVAC | Central | Fixed | Manual | 14F, 1BF | 4F, 5F | 13 |
| B2 | Yokohama | RC | MX | Central | Openable | None | 6F | 1F, 5F | 13 |
| B3 | Tokyo | SRC | HVAC | Central | Fixed | None | 9F | 3F | 13 |
| B4 | Yokohama | S, RC | MX | Local | Openable | None | 2F | 1F, 2F | 13 |
| B5 | Yokohama | RC, SRC | MX | Local | Openable | None | 7F, 2BF | 5F | 13 |
| B6 | Yokohama | S, RC | MX | Local | Openable | None | 2, 1BF | 1F | 13 |
| B7 | Tokyo | RC | MX | Local | Openable | None | 4F, 1BF | 1F, 4F | 13 |
| B8 | Tokyo | RC | MX | Local | Openable | None | 3F, 1BF | 1F | 13 |
| B9 | Tokyo | RC | HVAC | Central | Fixed | None | 8F, 3BF | 8F | 13 |
| B10 | Tokyo | S, SRC, PCa | HVAC | Central | Fixed | Automatic | 10F, 1BF | 6F, 7F | 12 |
| B11 | Tokyo | S, SRC, RC | HVAC | Central | Fixed | None | 24F, 4BF | 11F, 12F, 13F, 21F, 22F, 23F | 12** |

S: Steel, RC: Reinforced Concrete, SRC: Steel Reinforced Concrete, HVAC: Heating, ventilation and air conditioning, MX: Mixed mode (heating in winter and cooling in summer), *: The floor is counted by American system, F: Floor, BF: Basement floor, **: We have divided the floors in A, B & C groups (A: 22F, B: 21F, 23F, C: 11F, 12F, 13F) for monthly survey and each group is visited every 3 months i.e. each season. One small room of 21F is visited only once.

The type of mixed mode building is change-over. All mixed mode buildings have openable windows, and most of them (B4 ~ B8) are university office buildings. Generally, people open the windows in spring and autumn, and use cooling and heating in summer and winter. Two HVAC buildings have both manual and automatic natural ventilation openings. The surveyed floors were selected based on availability of occupants and permission given by the building managers.

## 2.2 Thermal Comfort and Occupant Behaviour Survey

Thermal comfort surveys were conducted and corresponding thermal measurements made in offices [19]. The indoor air temperature, globe temperature, relative humidity and air movement were measured 1.1m above floor level, away from direct sunlight, using a data logger (Fig. 1, Table 2). Outdoor air temperature and relative humidity were obtained from the nearest meteorological station. The thermal comfort survey was conducted in Japanese. The subjective scales are shown in Table 3. The ASHRAE scale is frequently used to evaluate the thermal sensation vote (TSV), but the words 'warm' or 'cool' imply comfort in Japanese, and thus the modified thermal sensation vote (mTSV) is also used to evaluate the thermal sensation (Table 3). To avoid a possible misunderstanding of 'neutral', it was explained in the questionnaire as 'neutral (neither hot nor cold)'. It is also said that the optimum temperature occurs on the cooler side in summer and on the warmer side in winter [12].

We conducted both transverse and longitudinal surveys in open-plan offices. This paper analyses only the data from the transverse surveys. Transverse surveys were conducted 1 day each month by researchers visiting each building with measurement instruments and with questionnaires filled by each subject. On each visit, one set of responses was collected from each subject. As for the method of collecting the data, the instruments were set up on the office table, and questionnaires distributed to all people seated near to the instruments (Fig. 1). While people were filling the questionnaire, the researcher recorded the common environmental controls and the physical data from them. Window opening, heating use and cooling use were recorded in binary form at the time of completing the questionnaire (0 = window closed or heating/cooling off, 1 = window open or heating/cooling on). We collected 4,660 thermal comfort votes from about 1350 people.

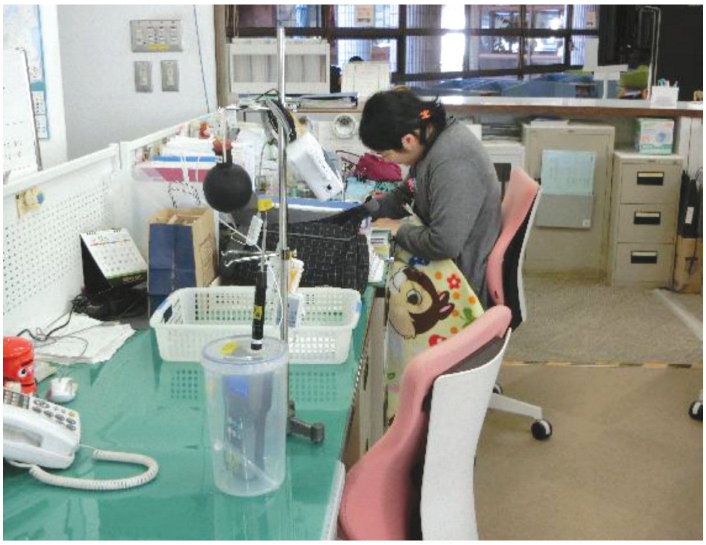

**Fig. 1: Photograph of the instrumentation and a subject completing the thermal comfort survey**

**Table 2:** Description of the instruments

| Parameter Measured | Trade Name | Range | Accuracy |
|---|---|---|---|
| Air temp., Humidity, $CO_2$ | TR-76Ui | 0 to 55 °C, 10% to 95% RH, 0 to 9,999 ppm | ±0.5 °C, ±5%RH, ±50 ppm |
| Globe temp. | Tr-52i | −60 to 155 °C | ±0.3 °C |
| | SIBATA 080340-75 | Black painted 75 mm diameter globe | - |
| Air movement | Kanomax, 6543-21 | 0.01 to 5.00 m/s | ±0.02 m/s |
| Illuminance | TR-74Ui | 0 to 130 klx | ±5% |

**Table 3:** Scale of modified thermal sensation vote (mTSV)

| No. | mTSV |
|---|---|
| 1 | Very cold |
| 2 | Cold |
| 3 | Slightly cold |
| 4 | Neutral (neither hot nor cold) |
| 5 | Slightly hot |
| 6 | Hot |
| 7 | Very hot |

### 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 [4, 6, 7, 14, 15, 25, 26].

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

$T_c$ is the estimated comfort temperature using the Griffiths' method (°C), $T_g$ is the indoor globe 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 [6, 7] and from Japan [19].

### 2.4 Estimating the Occupant Behaviour

Nicol and Humphreys [13] made use of logistic analysis to predict occupant control behaviour in naturally ventilated buildings. We have adopted this method here, using SPSS version 23 for the calculations. The relationship between the probability of windows being open or heating use or cooling use (p) and the outdoor air temperature ($T_o$) is of the form:

$$\text{logit}(p) = \log\{p/(1-p)\} = bT_o + c \quad (2)$$

$$p = \exp(bT_o + c)/\{1 + \exp(bT_o + c)\} \quad (3)$$

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

## 3. Results and Discussion

The data were divided into three groups. If heating was in use at the time of the survey visit, the data were classified as being in the heating mode (HT). If cooling was in use at the time of the visit, the data were classified as being in the cooling mode (CL). If neither heating nor cooling were in use, the data were classified as being in the free-running mode (FR). The CL and HT modes are distinct groups of data (generally CL used in summer and HT is used in winter), and need to be analysed separately. Thus the classification differs from that used in the CIBSE Guide, and in current standards ISO Standard EN 15251 and ASHRAE Standard 55. The mixed (MX) mode includes all of these three modes.

### 3.1 Outdoor and Indoor Temperature

The mean outdoor air temperatures during the voting were 20.7 °C, 24.9 °C and 10.4 °C for FR, CL and HT modes respectively [19]. The globe temperature is highly correlated with the indoor air temperature, and so the results can be presented using the indoor globe temperature alone [19]. The mean globe temperatures during the voting were 25.0 °C, 25.9 °C and 23.8 °C for FR, CL and HT modes respectively [19]. The Japanese government recommends indoor temperature of 20 °C in winter and 28 °C in summer respectively. The results show that the mean indoor temperatures during heating and cooling were quite different from those recommended. As shown in the Fig. 2, the seasonal range of the mean indoor temperature was quite small (about 5K), while there was a wide seasonal range of the monthly mean outdoor temperature (about 10K).

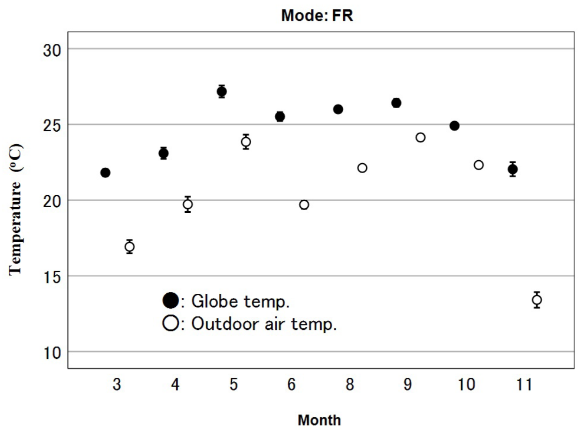


**Fig. 2: Monthly mean globe temperature and outdoor air temperature (at 95% confidence level: Mean±2S.E.)**

### 3.2 Window Opening

#### 3.2.1 Status of window opening

The mean 'open window' for all data is 0.23 (n=1230). When we compared by building, the mean value ranged from 0.02 to 0.51. The mean window opening is 0.68 (n=399), 0.03 (n=330) and 0.01 (n=501) for FR, CL and HT modes respectively. Interestingly, the mean window opening in UK office buildings was 0.70 in NV mode and 0.04 in AC mode [23]. The mean windows open in Pakistan office and commercial buildings was 0.33 in NV mode [25]. The results showed that the mean windows open is close to the UK and higher than the Pakistan. As the window opening is very low in the CL and HT modes, we shall limit the analysis to the FR mode.

### 3.2.2 Season and month

The proportion of open windows is highest in summer and lowest in spring (Fig. 3(a)). The proportion of open windows in autumn is significantly higher than that in spring. However, the indoor and outdoor air temperatures in autumn are slightly higher than that of spring (Fig. 3(b)), so more window opening would be expected. Evidently, the proportion of open windows gradually increases towards the summer months (Fig. 4). Conversely, it gently decreases towards the winter months as indoor or outdoor air temperature varies (Fig. 2).

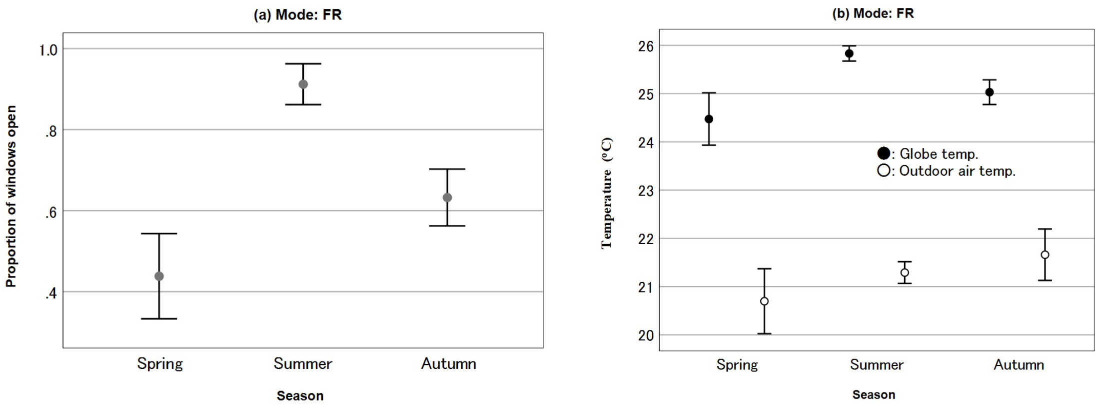


**Fig. 3: The proportion of open windows, globe temperature and outdoor air temperature in each season**

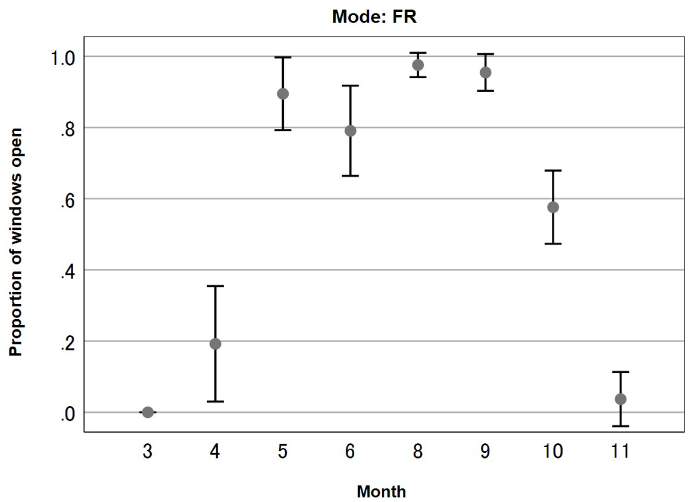


**Fig. 4: The proportion of open windows in each month (at 95% confidence level: Mean±2S.E.)**

### 3.2.3 Cooling effect of the open window

The potential of the open window is further analyzed in the context of indoor globe temperature or comfort temperature. The mean globe temperature for window open is 25.8 °C which is 1.9

K higher than that of the case of window closed (Fig. 5(a)). The mean comfort temperature for window open is 25.4 °C which is 1.5 K higher than that of the case of window closed (Fig. 5(b)). Brager et al. [2] found 1.5 K higher comfort temperature for the people in office buildings with access to window operation than the group without such access. It is interesting to note that we have also found the same results in Japanese offices. The temperature difference for the windows open and closed in spring is higher than in autumn (Fig. 5). The results showed that window opening is effective to increase the comfort temperature.

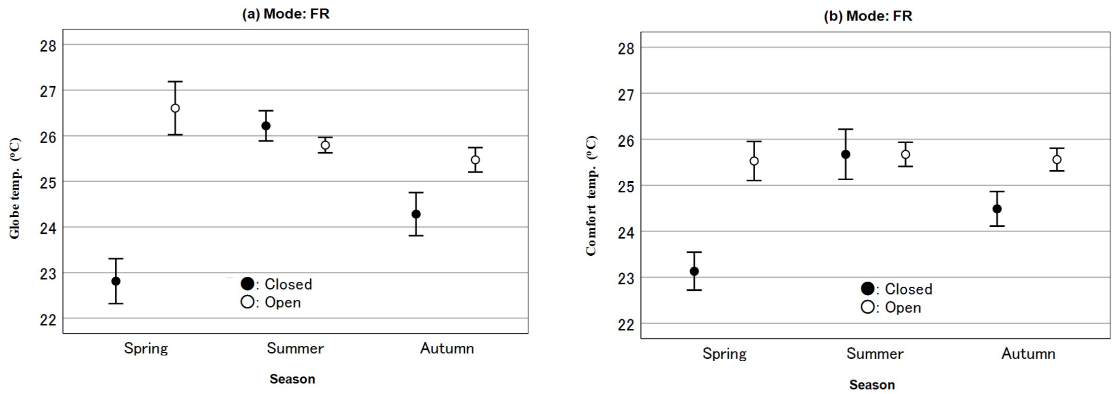


**Fig. 5: Seasonal variation of globe and comfort temperature for windows open and closed (at 95% confidence level: Mean±2S.E.)**

### 3.2.4 Development of an algorithm to predict window opening behaviour

In the previous sections, 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 Japanese offices. Such predictions are needed for the thermal simulation of buildings. The following regression equations were obtained for all data in between the windows open and the outdoor air temperature:

$$\text{logit(p)} = 0.507T_o\text{-}10.0 \text{ (n = 399, } R^2 = 0.27\text{, S.E. = 0.059, p < 0.001)} \quad (4)$$

where n is number of data, $R^2$ is Cox and Snell $R^2$, S.E. is standard error of the regression coefficient and p is significance-level of the regression coefficient.

In this study a regression coefficient of 0.507 is obtained when the open window and outdoor air temperature are regressed. Kyoto [11] and UK [23] studies returned the regression coefficients of 0.119 and 0.181 respectively when open window is regressed with outdoor air temperature. It seems that the regression coefficient of this research is higher than the previous research. As shown in the Fig. 6(a), the proportion of the windows open rises as the outdoor temperature rises. In order to analyze the window opening behaviour in MX mode, we conducted a Gaussian regression analysis using the following equations. We used this method because, due to cooling use, the proportion of window-opening gradually decreases above a certain outdoor temperature. Due to heating use, the proportion of window-opening is also gradually decreased below a certain outdoor temperature.

$$p = Ae^{Y} \quad (5)$$

$$Y = \{-(T_o-\mu)^2/2\sigma^2\} \tag{6}$$

where A is height of the peak, $\mu$ is x value of the center of the peak, $\sigma$ is controlling peak's width; A, $\mu$ and σ being constants. The regression equation of the proportion of open windows ($P_w$) obtained by using Gaussian function is shown in equation (7).

$$P_w=0.763\exp\{-(T_o-23.1)2/0.564\} \text{ (n=1230)} \tag{7}$$

The regression line which is calculated by equation (7) is shown in Fig. 6 (b). The temperature that results in the maximum value of $P_w$ is about 23°C.

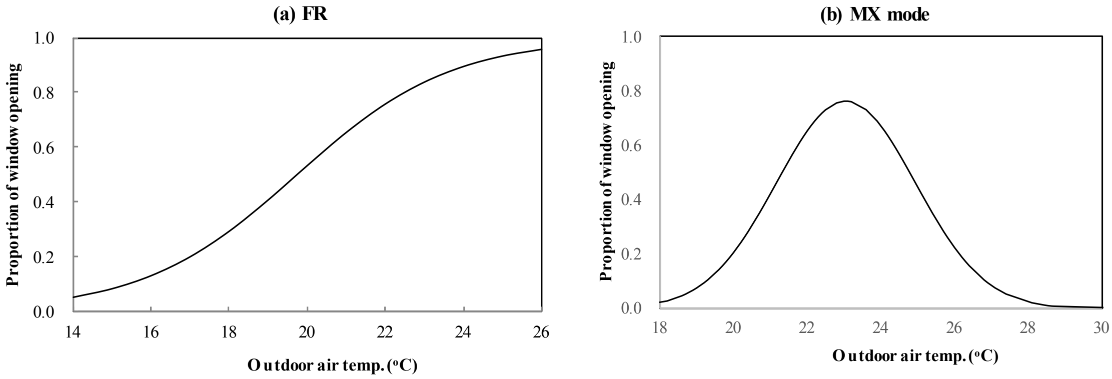


**Fig. 6: Relation between the window opening and outdoor air temperature**

### 3.3 Clothing Adjustments

Fig. 7 shows the mean clothing insulation in each mode. The mean clothing is 0.67 clo in FR mode which is slightly higher than CL mode and lower than HT mode. The results show that people adjusted their clothing considerably in each mode.

In order to predict the clothing insulation, regression analysis of the clothing insulation and outdoor air temperature is conducted. Fig. 8 shows the relation between the clothing insulation and outdoor air temperature with the 95% confidence interval of the individual clo-values in MX mode. The following regression equations were obtained between the clothing insulation ($I_{cl}$, clo) and outdoor temperature.

FR $I_{cl}=-0.030T_o+1.3$ (n=419, $R^2$=0.27, S.E. = 0.002, p<0.001) (8)

CL $I_{cl}=-0.006T_o+0.8$ (n=2488, $R^2$=0.08, S.E. = 0.0004, p<0.001) (9)

HT $I_{cl}=-0.007T_o+0.9$ (n=1692, $R^2$=0.01, S.E. = 0.002, p<0.001) (10)

MX $I_{cl}=-0.014T_o+1.0$ (n=4599, $R^2$=0.30, S.E.=0.0003, p<0.001) (11)

$R^2$ is coefficient of determination. The regression coefficients are negative for all equations. It shows that the clothing insulation decreases when outdoor air temperature is increased.

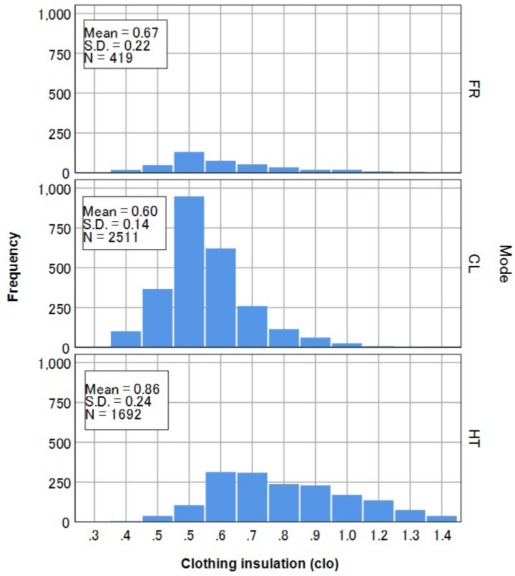


**Fig. 7: Distribution of clothing insulation**

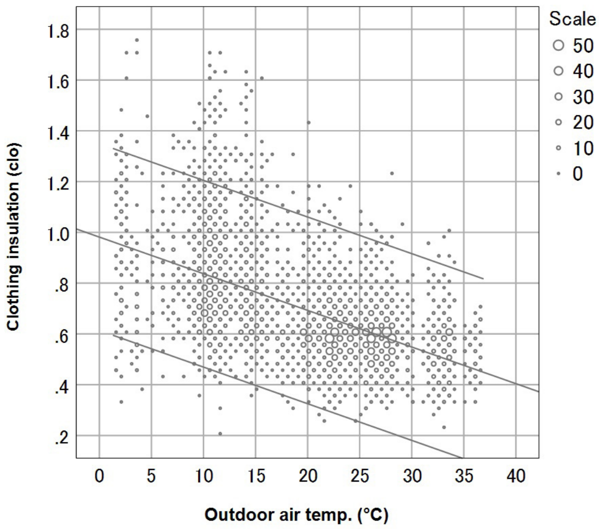


**Fig. 8: Relation between the clothing insulation and outdoor air temperature**

## 3.4 Heating and Cooling Use

In this section, we will analyze the active behaviour such as heating and cooling use. These behaviours are needed for the thermal simulation of buildings. The following regression equations were obtained for all data in between the heating use or cooling use and the outdoor air temperature:

Heating $\mathrm{logit}(p)=-0.839T_o+13.6$ (n=1241, S.E.=0.055, $R^2$=0.66, p<0.001) (12)

Cooling $\mathrm{logit}(p)=0.359T_o-8.5$ (n=1241, S.E.=0.024, $R^2$=0.37, p<0.001) (13)

These equations are presented in the Fig. 9. The proportion of the heating use rises as the outdoor temperature decreases, and the proportion of the cooling use rises as the outdoor temperature increases.

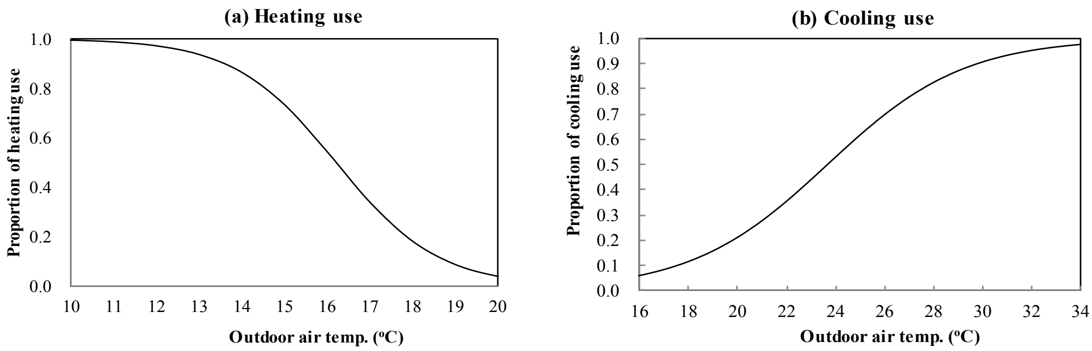


**Fig. 9: Relation between the heating use or cooling use and outdoor air temperature**

## 4. Conclusions

A thermal comfort survey and occupant behaviour survey in the Tokyo and Yokohama areas of Japan were conducted more than a year in 11 office buildings. The following results were found:

- The proportion of 'open window' in the free running mode (neither heating or cooling being used) is significantly higher than that of the air conditioned mode.
- The behavioural adaptations (window opening, clothing adjustments, heating/cooling use) are related to the outdoor air temperature.
- The behavioural adaptation predicted by regression analysis is in good agreement with the measured data. These findings can be applied to building thermal simulation to predict the behavioural adaptation, indoor temperature and energy use in office buildings.

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