Study on adaptive model and behavioural adaptation for thermal comfort of Japanese office buildings

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Abstract. This study focuses on the behavioural aspects of the occupants in Japanese office buildings. The behavioural adaptations such as window opening, heating/cooling use, clothing adjustments are important contributor factors for the adaptive thermal comfort. Therefore, understanding the behavioural aspects of the office workers can lead to have the guidelines to explain the mechanism of the adaptive model. The main aim of this study is to identify the differences in behavioural adaptation of the occupants in Japanese office buildings. Environmental parameters such as air temperature, relative humidity, and so on were measured in five mixed-mode office buildings located in Aichi prefecture were analysed for 15 months' survey with 35 occupants. Thermal comfort survey together with the occupants' behavioural survey were conducted in these office buildings. An adaptive relationship can be derived to estimate the indoor comfort temperature estimated by Griffiths method from the prevailing outdoor temperature. The results suggest that the proportion of heating and cooling use is related to the outdoor air temperature. The proportion of clothing adjustment is different for the different modes and are correlated to the outdoor air temperature. The acknowledge of the adaptive thermal comfort and the occupant behaviour of the selected buildings will be fruitful in designing the building with maximum thermal comfort in the future.

1 Introduction

Mixed-mode (MM) building operations are the office building having both naturally ventilation and the air-condition system strategies whenever required. The MM buildings have the potential to offer higher degree of thermal comfort as the occupants can prefer to choose the environment according to their desire [1]. Leaman and Bordass [2] found that comfort, perceived health, productivity was related to occupant control behaviour. If person feels too hot or too cold, they can adjust their clothing, postures and also the activities [3]. And broadening the adaptive opportunities for the occupants in response to the discomfort by giving them the permission to make the environmental adjustments themselves such as opening/closing window, fan use, clothing adjustment and heating and cooling use would be "bonus" point for the occupants to achieve their thermal comfort [4].

Adaptive principle states "if change occurs so as to produce discomfort, occupants react in ways which tend to restore their comfort" [5]. It means that the occupant always tries to regain their level of comfort when there is any unpleasant change occurs. The range of adaptive thermal environment is said to be wider than in laboratory experiments where the degree of freedom is limited [6]. It has been reported that in hot and cold environments, adaptation to the environment reduces the difference between the actual room temperature and the comfortable temperature, and accepts a wide range of temperature [6].

Heating, Ventilation, and Air Conditioning (HVAC) system is well equipped in Japanese office buildings. The indoor temperature is adjusted using the air-conditioning systems to help in maintaining the thermal comfort. However, only adjustment of the indoor temperature cannot determine whether the occupants are thermally comfortable with the existing environment

Table 1. Literature review on occupant behaviours

References	Area	Number of buildings	Mode of operation	Survey period	Behavioural adaptation
Goto et al. [9]	Sendai, Tsukuba, Yokohama	6	Mechanical heating and cooling	Jul. 2003- May 2005	Clothing insulation
Indraganti et al. [10]	Tokyo	4	AC mode	29 days, Jul. 4, 2012 through Sept. 11, 2012	Clothing insulation
Mustapa et al. [11]	Fukuoka	2	FR and CL	(Summer) 7 to 28 Aug. 2014	Clothing insulation
Takasu et al. [12]	Tokyo, Kanagawa	5	Air-conditioning (multiple packaged air conditioning unit system; zone control by occupants), Electric fan, Operable window	All seasons	Clothing insulation, Window-opening
Rijal et al. [7]	Tokyo, Yokohama	11	HVAC and MM	Aug. 2014 – Oct. 2015	Window opening, Clothing adjustments, Use of heating and cooling

AC : Air conditioning mode, HVAC : Heating, Ventilation, and Air Conditioning, MM : Mixed Mode, FR : Free-running mode, HT : Heating mode, CL : Cooling mode

because any discomfort experienced by the occupants will induce to the behavioural changes in order to be comfortable [7]. Also, field study of Japanese office buildings suggested that occupants had more opportunities to control their thermal conditions rather than in centralized HVAC office buildings [8]. It is necessary to have research on the behavioural adaptation in the Japanese office buildings.

Thermal comfort and behavioural aspects of an occupants are closely related to each other. The previous studies on the adaptive behaviour in the office buildings such as Goto et al. [9], Indraganti et al. [10], Mustapa et al. [11], Takasu et al. [12], and Rijal et al. [7]. Rijal et al. [7] have stated that adaptive behaviour (window opening, clothing insulation, proportion of heating and cooling use, etc.) are the main elements to affect thermal comfort of the occupants. However, the previous research is limited in some of the places in Japan as shown in Table 1.

This study aims to analyse the comfort temperatures of the occupants and the adaptive model of thermal comfort. Further it identifies the differences in behavioural adaptation of the occupant in Japanese office buildings and study on how the occupant would restore their thermal comfort for any changes in response to the outdoor air temperature.

2 Methodology

The field survey was conducted in Aichi prefecture located in the central part of Japan having the climate characterized by hot and humid summers, and relatively mild winters (Köppen climate classification Cfa, i.e. humid subtropical climate). Figure 1 shows the monthly mean of the outdoor air temperature and relative humidity obtained from the Nagoya meteorological station. The highest air temperature is 27.8 °C in August, and lowest 4.1 °C in January. The average relative humidity varies from 60 to 77 % in different months of the year. Overall, 16,410 comfort votes were collected in 15-months of survey periods.

2.1 Field investigation

Field studies were conducted in five mixed mode office buildings since July 2021 to September 2022. The chosen office buildings were of change-over mixed-mode type having operable door/windows and the HVAC systems depending on the seasons or the time of the day. Detailed information about the office buildings is further elaborated in Khadka et al. [13].

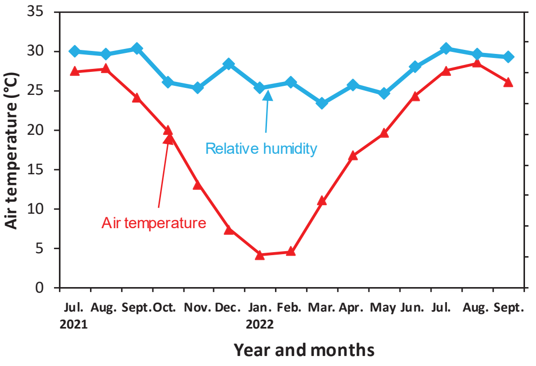


Fig. 1. Monthly mean outdoor air temperature and relative humidity in Nagoya [14].

2.2 Thermal comfort survey and occupant behaviour survey

This survey is 15-months longitudinal survey. The measurement of the environmental variables is air temperature and relative humidity by the digital instrument sensor, which is placed 1.1 m above the floor level, away from direct sunlight at ten-minute interval. Each office was visited every month. Quick responsive calibrated instruments were used to measure the indoor environment.

The questionnaire sheets were distributed to the office workers and the purpose of the survey and how to fill out the questionnaire were explained briefly. The occupants were asked to fill the questionnaire four times a day. Table 2 shows the scale used in the survey. Generally, the occupants voted 4 times a day: 2 times in the morning and 2 times in the afternoon. The survey was conducted in the Japanese language. One of the Japanese office building conducted the survey through PC. Heating use and cooling use were recorded in binary form during the survey (0= heating/cooling off, 1= heating/cooling on). Figure 2 shows survey questionnaire of the clothing insulation.

Table 2. Scale of thermal sensation vote

No.	Scale
1	Very cold
2	Cold
3	Slightly cold
4	Neutral
5	Slightly hot
6	Hot
7	Very hot

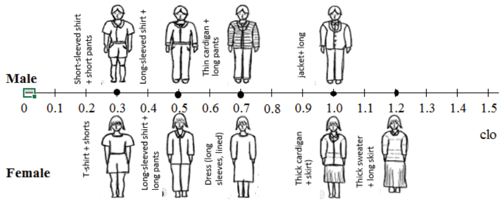


Fig. 2. Questionnaire of the clothing insulation

2.3 Estimation of the occupant behaviours

To predict the occupant behaviours, we used logistic regression analysis. Nicol and Humphreys [15] used logistic analysis and predicted the occupant's behaviour in naturally ventilated buildings. In this study the relationship between the probability of heating or cooling use (P) and the outdoor air temperature are shown in the following equation:

$$\text{logit}(P) = \log\{P/(1-P)\} = b\,T_{out} + c \quad (1)$$

$$P = \exp^{(b\,T_{out} + c)} / \{1 + \exp^{(b\,T_{out} + c)}\} \quad (2)$$

where, exp (exponential function) is the base of the natural logarithm, b is the regression coefficient, T_{out} is the outdoor air temperature (°C) and c the constant in the regression equation.

3 Results and discussion

Collected data from five mixed-mode office buildings are categorized into three groups i.e. if heating was used at the time of survey, the data were classified as heating mode (HT), if cooling was used during survey then the data were classified as cooling mode (CL) and when no heating or cooling system were active, the dataset were classified as free-running mode (FR).

3.1 Outdoor and indoor air temperature

During the voting, the mean outdoor air temperature was 19.4 °C, 9.9 °C, 29.0 °C for FR, HT and CL respectively. As shown in the Figure 3, globe temperature is highly correlated with the indoor temperature, hence we presented the mean globe temperature which was 25.5 °C, 24.6 °C, 24.4 °C for FR, HT, CL modes respectively as shown in Figure 4. In 2005, Japanese government recommended indoor temperature of 20 °C in winter and 28 °C in summer. In this case, mean indoor temperatures during heating mode and cooling mode were 3~4 °C different than the recommended values. However, the result is similar to the previous study in the Kanto region [7].

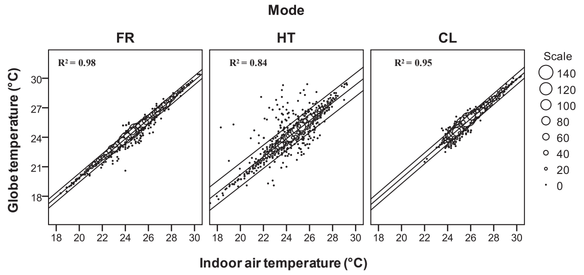


Fig. 3. Relationship between globe temperature and indoor air temperature

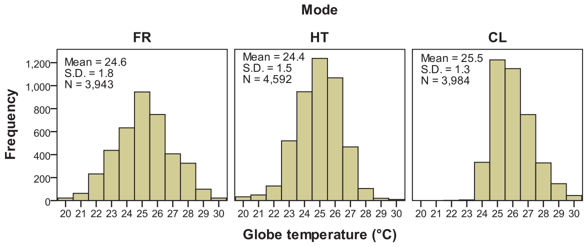


Fig. 4. Distribution of globe temperature

3.2 Comfort temperature by Griffiths' method

Griffiths' method is widely used method to determine the comfort temperature ranges in the buildings. Considering the occupants' thermal sensation votes in correspondence with measure indoor globe temperature, comfort temperature is predicted using equation.

$$T_c = T_g + (4 - \text{TSV}) / a$$

where, T_c is comfort temperature (°C) and a is Griffiths' constant (= 0.50).

The previous studies [16] show that when using each Griffiths' constant (0.25, 0.33 and 0.50), there was hardly any differences in the results obtained for the mean comfort temperature. Therefore, we used Griffiths' constant as 0.50 to estimate the comfort temperature similar to other studies [7]. The comfort temperature calculated using a coefficient 0.50 is a representation of 2 °C rise for a unit change in thermal sensation vote.

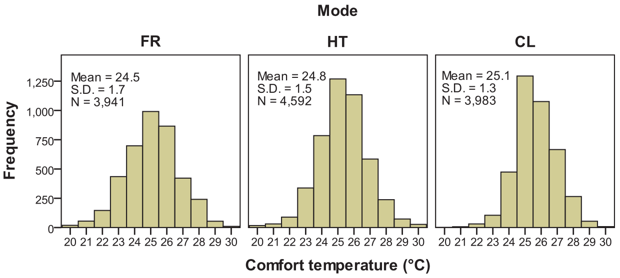


Fig. 5. Distribution of comfort temperature

The mean comfort temperature obtained by the Griffiths method are 24.5 (FR mode), 24.8 (HT mode) and 25.1 (CL mode), which are very similar to indoor globe temperature (Fig. 4 and 5). Even though the Japanese government recommends an indoor temperature 28°C for cooling and 20°C for heating, it was found that in these buildings the comfort was 4.8 °C higher in HT mode and 2.9 °C lower in CL mode.

3.3 Relating the comfort temperature to the outdoor temperature

3.3.1 Running mean outdoor temperature

The running mean outdoor temperature can be calculated using following equation from McCartney and Nicol [17]:

$$T_{rm} = \alpha T_{rm\text{-}1} + (1 - \alpha)\, T_{od\text{-}1} \qquad (3)$$

where $T_{rm\text{-}1}$ is the running mean outdoor temperature for the previous day (°C); and $T_{od\text{-}1}$ is the daily mean outdoor temperature for the previous day (°C). "α" is a constant between 0 and 1 that defines the speed at which the running mean responds to outdoor air temperature. The ASHRAE [18] standards recommend the value of α between 0.60 and 0.90 however McCartney and Nicol [17] found that the correlation between comfort temperature and outdoor temperature is almost constant in these ranges, so the value for α is chosen to be 0.8 used in the derivation of the CEN [19] standard.

3.3.2 Linear regression equations

An adaptive model relates indoor comfort temperature to outdoor air temperature [5, 19, 20] . In this section we have calculated the linear regression equation between the comfort temperature obtained by the Griffiths' method and the running mean outdoor air temperature as shown in the Figure 6.

FR mode $T_c = 0.14\ T_{rm} + 22.1$ (4)
($N= 3951$, $R^2 = 0.112$, S.E. = 0.006, $p < 0.001$)
CL and HT mode $T_c = 0.01\ T_{rm} + 24.7$ (5)
($N= 12{,}252$, $R^2 = 0.005$, S.E. = 0.001, $p < 0.001$)

where, S.E. is the standard error of the regression coefficient.

The coefficient of determination (R^2) is low which is similar to the field study carried out in Tokyo and Yokohama of Japan [7].

The regression coefficient and correlation coefficient is higher in FR mode than the CL or HT mode however it is lower than CEN standard [19] (FR=0.33) and CIBSE Guide [21] (HT and CL = 0.09). These results are also lower than previous studies done in Japanese offices in Tokyo and Yokohama (FR = 0.21; CL and HT = 0.07) [7]. It may be because of the differences of occupant's behaviours and the climatic variations of different regions in Japan.

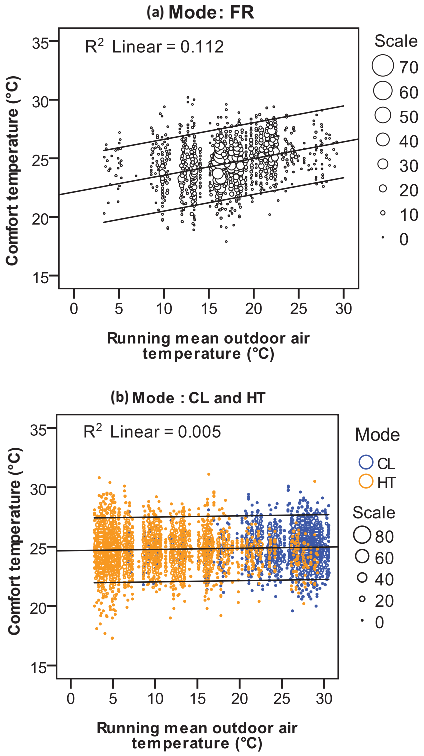


Fig. 6. Relationship between comfort temperature and running mean outdoor temperature: **(a)** free-running (FR) mode; and **(b)** cooling (CL) and heating (HT) modes.

3.4 Occupant behaviours

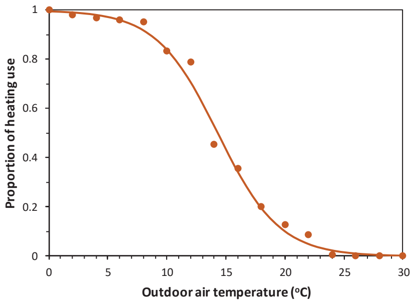
3.4.1 Heating use

In this section, we analysed the heating use in the mixed mode office buildings. Equations obtained by using logistic regression analysis are shown in Table 3. These equations are drawn in the Figure 7. We have also plotted the actual heating use which is binned at 2 °C interval of outdoor air temperature in Figure 7 (a). The results indicated that the logistic model is well fitted to the actual heating use data. The occupant starts using the heating when the outdoor air temperature starts dropping from 18 °C similar to the previous studies of Kanto area which had resulted as 17 °C [7]. Trend of proportion of heating use for each building is similar to overall trend Figure 7 (b). Equations obtained from logistic regression analysis can be used to estimate and control the heating use in similar office buildings.

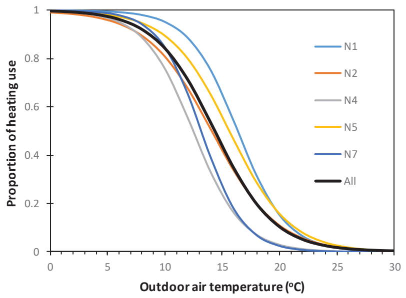
Table 3. Regression equation for each and all buildings for heating use

Building code	Equations	N	R^{2*}	S.E.	p
N1	logit(P)= -0.470 T_{out} +7.7	3567	0.57	0.018	<0.001
N2	logit(P)= -0.354 T_{out}+5.0	3304	0.52	0.012	<0.001
N4	logit(P)= -0.464 T_{out}+5.8	2507	0.55	0.020	<0.001
N5	logit(P)= -0.383 T_{out}+6.0	2307	0.54	0.016	<0.001
N7	logit(P)= -0.538 T_{out}+7.1	985	0.57	0.042	<0.001
All	logit(P)=-0.384 T_{out} +5.5	12670	0.54	0.007	<0.001

P: Proportion of heating use, N: Number of the sample, R^{2*}: Cox and Snell R^2, S.E.: Standard error of the regression coefficient and p: Significant level of regression coefficient.



(a) All office buildings



(b) All and each office buildings

Fig. 7. Proportion of heating use in relation to outdoor air temperature

3.4.2 Cooling use

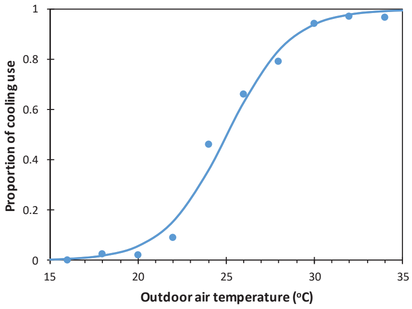
Unlike heating use in the buildings, since we had the dataset of 15-months, we also predicted the cooling use in the offices. Logistic regression equation obtained between the cooling use and outdoor air temperature are in the Table 4.

The equation is drawn in the Figure 8. We have binned the actual cooling use at 2 °C interval of outdoor air temperature and plotted on the Figure 8(a). The result indicated that the logistic regression is well fitted to the actual cooling use data. The result showed that the proportion of cooling use increases with increase in outdoor air temperature where the occupant started to use the cooling system when the outdoor temperature rises from 22.5 °C which is similar to [7].

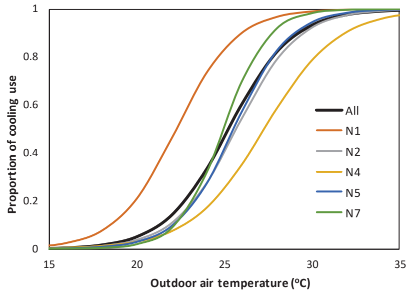
Table 4. Regression equation for each and all buildings for cooling use

Building code	Equations	N	R^{2*}	S.E.	p
N1	logit(P)= 0.588 T_{out} -13.8	3566	0.61	0.022	<0.001
N2	logit(P)= 0.572 T_{out} -14.7	3303	0.55	0.025	<0.001
N4	logit(P)= 0.480 T_{out} -13.1	2505	0.45	0.024	<0.001
N5	logit(P)= 0.634 T_{out} -16.2	2305	0.52	0.036	<0.001
N7	logit(P)= 0.796 T_{out} -19.9	988	0.61	0.070	<0.001
All	logit(P)= 0.555 T_{out} -14.0	12667	0.57	0.012	<0.001

P: Proportion of heating use, N: Number of the sample, R^{2}*: Cox and Snell R^2, S.E.: Standard error of the regression coefficient and p: Significant level of regression coefficient.



(a) All office buildings



(b) All and each office buildings

Fig. 8. Proportion of cooling use in relation to outdoor air temperature

3.4.3 Clothing adjustments

The mean clothing insulation is 0.66 clo, 0.84 clo, 0.66 clo for FR, HT, CL modes, respectively. The results show that the occupant chooses the clothing according to the modes, months and by gender too.

Figure 9 shows the scattered plot of the clothing insulation and the outdoor air temperature. We have also shown regression lines and 95 % confidence interval of the individual data on the figure. The regression equations are shown in Table 5. The regression coefficient is negative which clarify that the clothing insulation decreases with increase in outdoor air temperature. The result is similar to the previous research [9, 10, 12].

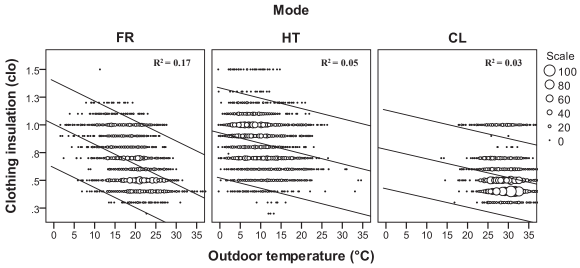


Fig. 9. Relationship between clothing insulation and outdoor air temperature

Table 5. Regression equation of clothing insulation and outdoor air temperature

Mode	Equation	N	R^2	S.E.	p
FR	$I_{cl}= -0.018\, T_{out} + 1.0$	3979	0.17	0.001	<0.001
HT	$I_{cl}= -0.009\, T_{out} + 0.9$	4695	0.05	0.001	<0.001
CL	$I_{cl}= -0.008\, T_{out} + 0.8$	3988	0.03	0.001	<0.001

I_{cl} : Clothing insulation (clo), N: Number of the sample, R^2: Coefficient of determination, S.E.: Standard error of the regression coefficient and p: Significant level of regression coefficient.

4 Conclusions

Having analysed the adaptive behaviours of the occupant in five mixed mode buildings in Aichi prefecture, the following conclusions are obtained.

1. The mean globe temperature during the survey was found 25.5 °C, 24.6 °C, 24.4 °C for FR, HT, CL modes respectively. This shows that the Japanese government recommended indoor temperature as 20 °C for winter and 28 °C for summer, and thus they are about 3~4 °C different than the recommended values.
2. The regression coefficient of the adaptive model (i.e. the relation between comfort temperature and running mean outdoor temperature (FR = 0.14; CL and HT = 0.01) are lower than CEN standard (FR = 0.33) and CIBSE Guide (CL and HT = 0.09).
3. Occupants conducted various behavioural adaptation like heating use, cooling use and clothing adjustments. The heating use is higher when the outdoor air temperature is low. Cooling use was found higher when the outdoor temperature is high. Clothing insulation is lower when the outdoor temperature is high. Overall, these behaviours are related to the outdoor air temperature.

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