Thermal comfort and occupant adaptive behaviour in university offices with cooling and free running modes

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This paper presents results of a small-scale field survey of occupant thermal comfort and adaptive behaviour, conducted in university office buildings in Fukuoka, Japan (August 2014). A comparison was made between offices with cooling (AC) and free running (FR) modes. Indoor environmental conditions were measured, simultaneously with administration of a questionnaire survey. Most Predicted Mean Vote (PMV) values were higher than Thermal Sensation Vote (TSV) values for both cases. This indicates that the PMV model over-predicted actual thermal response. The thermal response in FR offices was found to be more sensitive than in those with AC; additionally, respondents could tolerate a narrower range of variation in indoor operative temperature. Occupants' adaptive behaviours in AC office were more limited compared to those of respondents with FR. This indicates amenable thermal conditions in A/C-controlled indoor environments, with occupants having no wish to make changes.

Keywords: thermal comfort, cooling mode, free running mode, adaptive behaviour, PMV, TSV

Introduction

User satisfaction is an important part of measuring a building's performance, as people spend over 80% of their time in indoor environments. Many surveys have shown that thermal comfort is one of the most important aspects influencing occupant perception. As a result, air conditioners have become an essential feature of buildings, creating and maintaining thermally comfortable indoor conditions during working hours, with relatively homogeneous air temperature. However, each individual working in an office environment may experience different thermal sensations, therefore behaving in different ways in order to mitigate thermal discomfort (Karjalainen, 2009). Previous studies, the field analysis showed that the acceptability of the thermal environment strongly depends on occupant behaviour, such as changing clothes, taking a drink, switching on/off air conditioners or fans, and actively operating windows, blinds, or doors. The adaptive comfort models could provide a wider range for comfort temperature which means less cooling requirements for the unavoidable air conditioning conditions. The energy and environmental policy could have a significant need to meet for new buildings by raising the summer set point temperature in order to reduce electricity consumption (Yang et al., 2014).

After the Great East Japan Earthquake 2011, the Fukushima Daichi nuclear power station involved with critical damage resulted in energy shortage. The Japanese government mandated a 15% peak-power reduction for large commercial buildings (Tanabe et al., 2013). These energy cuts are becoming one of the issues for air conditioning system usage behaviour, which the occupants' thermal comfort is also highly concerned. Strategy to reduce electricity cost in air conditioning system could be done by using the high temperature setting which that would be valuable (Karyono and Bahri, 2005).

In hot and humid countries, the wasteful work style of occupants in office buildings tends to involve air conditioners being set at the lowest temperature, thus leading to higher energy consumption (Hong and Lin, 2012). In the southern area of Japan also experiences similarly hot and humid weather during summer months. Despite this, the aforementioned wasteful behaviour is not exhibited by the Japanese, since the COOL BIZ campaign in the country recommends that room temperature be set to 28 ^{0} C, possibly at the maximum extent of a comfortable temperature range. This strategy might be effective for reducing energy consumption from air conditioning systems, although occupant comfort should also be taken into consideration since this strongly affects productivity.

The main objective of this research was therefore to investigate occupant thermal comfort and adaptive behaviours in indoor office buildings with cooling (AC) and free running (FR) modes located in Fukuoka during the summer season.

Methods

Building and occupants information

Studies were conducted within two university office buildings located on the Chikushi Campus of Kyushu University, Fukuoka, Japan, during the summer season (from 7–28 August, 2014). Table 1 summarizes general information about the buildings and their occupants.

Table 1: **Summary of conditions in offices with cooling (AC) and free running (FR) modes**

Building code	No. of occupants		Type of ventilation	Window blind position	Remarks
	Male	Female			
E-CA	1	3	Split-type A/C with mechanical-aided stand fans	Open	AC
E-GA	1	6	Split-type A/C with mechanical-aided stand fans	Close	
F-L1	4	2	Split-type A/C with mechanical-aided stand fans	Open	
F-L2	7	4	Split-type A/C with mechanical-aided stand fans	Open	FR

The first building was comprised of two administrative offices referred to as E-CA and E-GA, while the second building included two researcher offices, referred to as F-L1 and F-L2. Generally, occupants of E-CA, E-GA and F-L1 operated both the A/C and the mechanical-aided fan. These offices herein after referred to as cooling mode (AC) office. The situation was different in F-L2, where occupants preferred to use mechanical-aided stand fans instead of switching on the A/C; as this laboratory implemented the energy consumption savings campaign. This situation is referred to as a free running (FR) office. Occupants of this room could not control the indoor environmental climate but were free to adjust their environment in terms of clothing, use of stand fans, and so on.

A total of 303 responses from 28 individuals were obtained and only eight responses were omitted due to invalid questionnaire feedback. Respondents in AC office were composed of 6 males (35.3%) and 11 females (64.7%), whereas respondents in FR office were 7 males (63.6%) and 4 females (36.4%). The average age of males in AC office was 32 years old (standard deviation, SD = 17) and that of females was 40 years old (SD = 11); in FR office, the average age of males was 26 years old (SD = 5), while that of females was 27 years old (SD = 4). Field measurements and questionnaire surveys were carried out simultaneously, two times per day over all working days in the morning and afternoon, between 10:00 am and 4:00 pm.

Indoor measurements

Four indoor environmental parameters were measured: air temperature (t_a), relative humidity (RH), globe temperature (t_g), and air speed (v_a). t_a and RH were measured using a thermo-recorder data logger (Hobo U12-013) at 1 min intervals, while v_a was recorded using a hot wire anemometer (KANOMAX climomaster 6501) at 10 s time intervals. Globe temperature was also measured using the data logger (HOBO U12-013) with an external temperature sensor (TMC1-HD), at 1 min intervals. The temperature probe was installed within a black painted table tennis ball, as shown in Fig. 1 (a). All instruments were clamped into a device placed at a height of 1.1 m above the floor, as shown in Fig. 1 (b). Outdoor air temperature was measured using the thermo-recorder data logger (HOBO U12-013) equipped with a solar radiation shield, as shown in Fig. 1 (c); this was placed outside the office building. All thermo-recorders had measurement accuracy of ± 0.35 °C (from 0–50 °C) and were calibrated against a reference thermocouple type-k using data logger GRAPHTEC GL820, with measurement accuracy of ± 0.0005 °C (from -100–1370 °C).

To take the measurements, the devices were placed at three different locations in each office room. The average value of these three positions was used to represent the thermal conditions in the office room. Both mean radiant temperature (T_{MRT}) and operative temperature (T_{OP}) were estimated using the following expression (Auliciems and Szokolay, 2007):

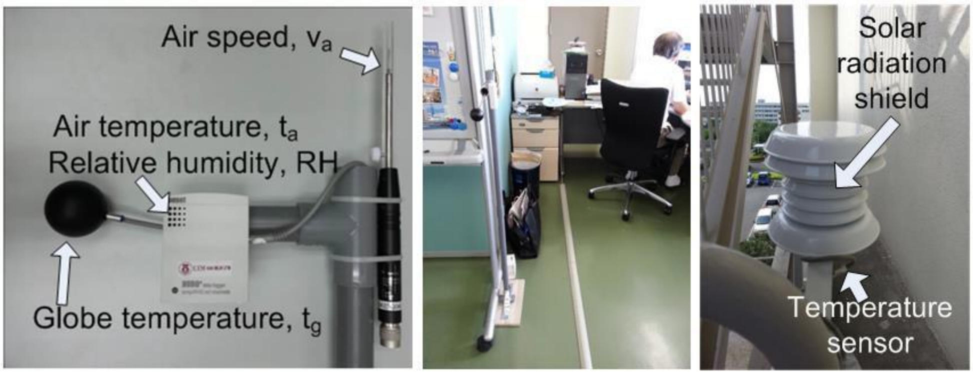
$$T_{MRT} = \left[\left(t_g + 273 \right)^4 + \frac{\left(1.10 \times 10^8 \times v_a^{0.6} \right)\left(t_g - t_a \right)}{\left(\varepsilon \times \mathrm{D}^{0.4} \right)} \right]^{0.25} - 273 \qquad (1)$$

where t_g is the globe temperature (°C), v_a is the air speed (m/s), t_a is the air temperature (°C), ε is the emittance that was equal to 0.95, and D, which was equal to 40 mm, represents the diameter of the black coloured table tennis ball that was used to measure the t_g.

The ASHRAE Standard 55 (2013) mentions that simple averaging can yield acceptable results for T_{OP} as follows:

$$T_{OP} = \frac{\left(T_{MRT} + t_a \right)}{2} \qquad (2)$$

where T_{MRT} is the mean radiant temperature and t_a is the air temperature.



(a) (b) (c)

Figure 1: (a) Equipment set-up for measuring t_a, RH, t_g, and v_a, (b) Sensors were placed at a height of 1.1 m above floor level, (c) Thermal recorder with solar radiation shield for measuring outdoor temperature

The device was placed at three different locations in each office room, as shown in Fig. 2 (a–d), except for the hot wire anemometer, which was placed at only one location.

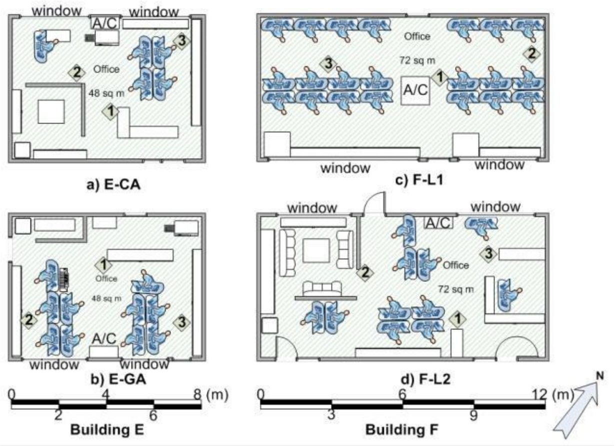


Figure 2: Layout plan of measurement locations in (a) E-CA – cooling (AC) (b) E-GA – AC (c) F-L1 – AC and (d) F-L2 – free running (FR). Numerals 1, 2, and 3 refers to sensor locations.

Questionnaire survey

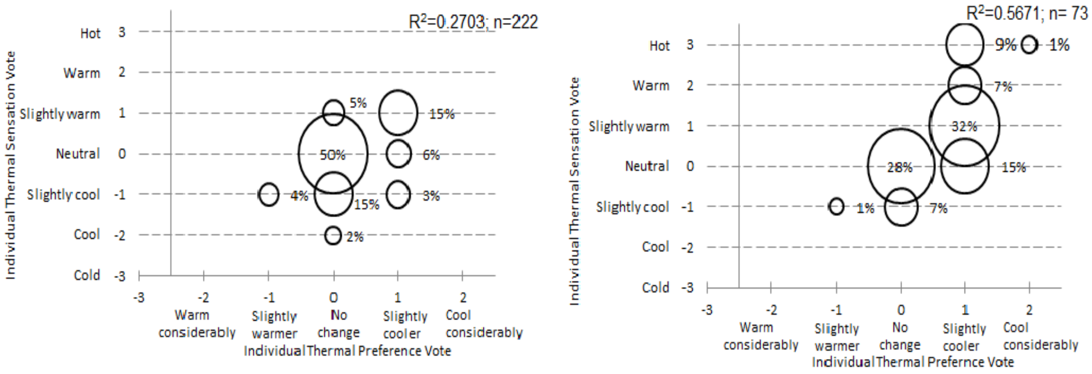
Questionnaires were written in English and Japanese. The questionnaire had four main sections, based on the survey form in ASHRAE Standard 55 2010. The first section concerned demographic information (such as gender, age, and current health conditions). The second comprised the standard seven-point ASHRAE thermal sensation scale, thermal acceptability questions, thermal preferences is based on Nicol's five-point scale, a four-point air movement perception question, and a six-point comfort vote question. The range for the thermal sensation vote (TSV) spanned cold (-3) to hot (+3). The thermal acceptability question asked occupants whether thermal conditions were 'acceptable' or 'unacceptable'. The third section concerned adaptive methods, with the final section consisting of a clothing insulation checklist. The adaptive methods question asked respondents to indicate which, of a range of options, they adopted to address hot/cold discomfort; options included switching on/off A/C systems or fans, closing/opening doors and windows or window blinds, taking off/putting on jacket, drinking, or just doing nothing.

The metabolic rate value was assumed to be 1.2 Met for sedentary office workers. The Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD), based on ISO 7730, were applied by using four indoor environmental variables in conjunction with two personal parameters (e.g., metabolic rate and clothing insulation).

Results and Discussion

Thermal sensation and preference votes

Figs. 3 (a) and (b) show the average percentage of respondents' thermal preference vote in relation to their TSV for AC and FR offices; it is found that the correlation coefficient between TSV and TPV is 0.2703 and 0.5671 for AC and FR offices, respectively.



(a) **(b)**

Figure 3 Average percentage of thermal preference vote (TPV) in relation to TSV in (a) AC office (E-CA, E-GA and F-L1) and (b) FR office (F-L2)

In AC office, about 50% of respondents who voted “neutral 0” on the thermal sensation scale also voted “no change 0” on the thermal preference scale. This shows that respondents were satisfied with their current neutral thermal sensation and did not want to change conditions. In FR office, only 28% of respondents selected this same option; 32% of respondents who described their thermal sensation as “slightly warm 1” preferred “slightly cooler 1”. In general, in terms of the correlation between TSV and TPV, respondents in AC office would mostly prefer no change, while occupants of FR office would prefer slightly cooler conditions. This might be due to the thermostat settings for A/C systems being in the range of 27–28 °C in AC office; meanwhile occupants in FR office were able to mitigate their thermal discomfort by switching on fans, opening windows or doors, or through other adaptive methods.

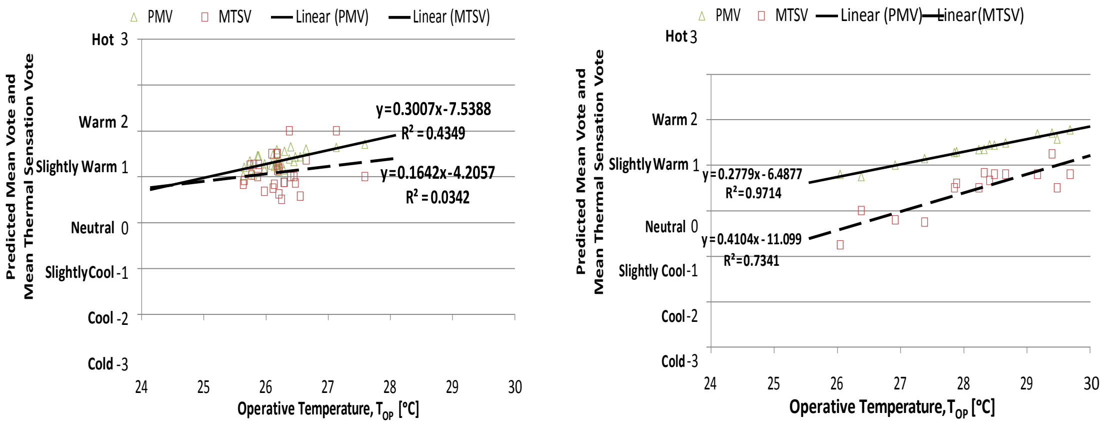
Mean thermal sensation vote (MTSV) and Predicted Mean Vote (PMV)

Regarding the indoor thermal comfort indices, Fig. 4 (a) and (b) plot average PMV and MTSV values versus T_{OP} for AC and FR office. The MTSV was calculated for each group and every measurement conducted using the following equation:

$$MTSV = \left(\frac{\sum_{-3}^{+3} (N_i \times TSV_i)}{Total\ Number\ of\ Thermal\ Sensation\ \ Vote} \right) \qquad (3)$$

where N_i is the number of i vote and TSV_i is the scale from seven point ASHRAE thermal sensation vote.

Neutral temperatures of MTSV and PMV for AC office were 25.6 °C and 25.1 °C, respectively. Similarly, neutral MTSV and PMV temperatures for FR office were 27.0 °C and 23.3 °C, respectively. By analysing linear regression for both cases, it can be noted that neutral temperatures for MTSV are higher than expected on the basis of PMV values. This implies that Japanese people have high tolerance for the indoor environment.



(a) **(b)**

Figure 4: Regression analysis of average PMV and MTSV with T_{OP} in (a) AC office and (b) FR office

Regression equations for MTSV and PMV were in the following forms:

i. AC office

$$MTSV = 0.1642T_{OP} - 4.2057; \qquad R^2 = 0.0342 \qquad (n = 30) \qquad (4)$$

$$PMV = 0.3007T_{OP} - 7.5388; \qquad R^2 = 0.4349 \qquad (n = 30) \qquad (5)$$

ii. FR office

$$MTSV = 0.4104T_{OP} - 11.099; \qquad R^2 = 0.7341 \qquad (n = 15) \qquad (6)$$

$$PMV = 0.2779T_{OP} - 6.4877; \qquad R^2 = 0.9714 \qquad (n = 15) \qquad (7)$$

The slopes in Eqs. (4) to (7) represent the extent of thermal sensation change with T_{OP}. Regression can quantify thermal responses with occupants' thermal sensitivity to T_{OP}. This implies that if one unit change of sensation scale is desired, the corresponding specific change in air temperature in degrees Celsius can be deduced, based on the observed gradient. The slopes of regression equations can therefore be viewed as respondents' sensitivity with respect to T_{OP}. From Eqs. (4) and (5), it can be noted that the slopes of linear fit of MTSV and PMV in AC office are about 0.1642 unit/°C and 0.3007 unit/°C, respectively. The slopes of MTSV and PMV in FR office are about 0.4104 unit/°C and 0.2779 unit/°C, respectively, as shown in Eqs. (6) and (7). The slope of linear fit of MTSV is more than that of PMV, especially in FR office and it contradicted in AC office. This phenomenon indicates that thermal response in the FR office is more sensitive than in AC office. Vice versa, the value per sensation scale to temperature range of the MTSV is 6.1 °C/unit, greater than that of PMV (3.3 °C/unit) for AC office. Contradicted in FR office, the value per sensation scale to temperature range of the MTSV is 2.4 °C/unit lower than that of the PMV (3.6 °C/unit).

The result implies that respondents in AC office can tolerate broader variation in T_{OP}, more in accordance with the MTSV than with the PMV model.

Griffiths' Method of comfort temperature

The comfort temperature, T_C is estimated based on TSV data using Griffiths' method (Rijal, 2014).

$$T_C = t_a + \frac{(0-c)}{a} \tag{8}$$

where t_a is the indoor air temperature (°C) or globe temperature (°C), *c* is the TSV voting and *a* is the regression coefficient.

In applying the Griffiths' method, Nicol et al. (1994) and Humphreys et al. (2013) used the constants 0.25, 0.33 and 0.50 for a 7 points thermal sensation vote. The comfort temperature was estimated by using these constant as regression coefficients. Table 2 displayed that the mean comfort temperature of each coefficient is not very different, so with 0.50 coefficient is adopted and comfort temperature calculated is used for further analysis.

Table 2. **Comfort temperature predicted by Griffiths' method**

Mode	Regression Coefficient	Comfort indoor temperature, T_c n	Mean	S.D
AC	0.25	222	26.59	2.94
	0.33	222	26.52	2.27
	0.50	222	26.44	1.56
FR	0.25	73	26.27	2.82
	0.33	73	26.73	2.09
	0.50	73	27.23	1.37

AC: Cooling mode; FR: Free running mode; n: number of sample; S.D: Standard deviation

The mean comfort air temperature by Griffiths' method is 26.44 °C and 27.23 °C in AC and FR office, respectively. The comfort temperature as estimated by the Griffiths' method is more appropriate since the mean comfort temperature is comparable to the indoor temperature when voting "0 neutral". The comfort temperature in summer was found quite similar with existing research (Rijal, 2014).

Adaptation behaviour

Fig. 5 shows adaptation behaviours of occupants of AC and FR offices. In AC office, about 65% of the respondents voted to "do nothing". Approximately 13% voted for "switch-on/off A/C" in AC office, with other options selected by less than 14% of respondents.

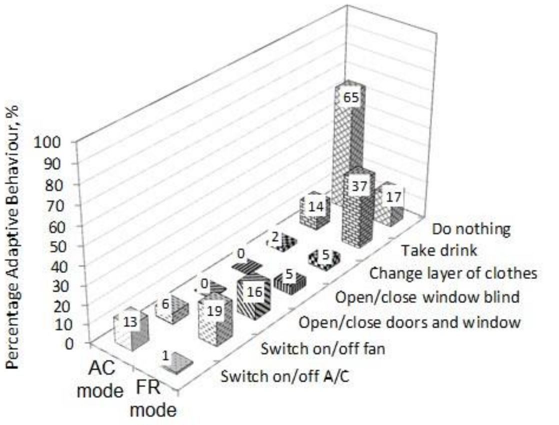


Figure 5 Percentage of adaptive behaviour in AC and FR office

However, there were differences in the FR office, where 37% respondents would like to drink to adjust their thermal discomfort, to rapidly cool their core body temperature. The next most-selected option (19% of respondents) was switching on the fan, while 16% of respondents preferred to open/close doors and windows. A higher percentage of respondents adapted through behavioural methods in FR office than in AC offices, as reported from field studies in Chennai and Hyderabad, India (Indraganti et al., 2014). Overall, this adaptive behaviour indicates that most occupants of AC offices are more satisfied with the AC environment and can focus more on their work, as compared to occupants of FR office, who tend to adjust their thermal discomfort to within a comfortable thermal zone.

CONCLUSION

This study presented the results of thermal comfort field measurements conducted in two educational buildings (AC and FR offices) in Fukuoka, Japan during the summer, August 2014. The neutral temperature of linear regression for TSV is higher than expected by PMV values in both cases. However, the neutral temperature of TSV in AC office is 1.4 °C, slightly lower than that in FR office. This indicates that the thermal response of occupants of FR office is more sensitive than that of occupants of AC office. Respondents can therefore tolerate only a narrow variation in T_{OP}. In terms of overall comfort, respondents in AC office were mostly satisfied with their neutral thermal sensations and did not want to make changes, as illustrated by their adaptation behaviour (56% of respondents opting to do nothing). Meanwhile, in FR office, respondents preferred slightly cooler environments, since most operative temperatures were above 28 °C, beyond a comfortable temperature range.

From observation, it was also noted that the Japanese would like to combine use of mechanical-aided fans with a low AC cooling load. This could be significant for energy saving, and an effective way for cooled air to flow uniformly inside the working area in an office. Furthermore, the high tolerance and flexibility of the occupant to adapt with hot environment occupant might be influenced by other occupants whose not prefer to use AC system. It implies that the comfort temperature is also affected by psychological adaptation.

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