INVESTIGATION OF THE THERMAL COMFORT AND PRODUCTIVITY IN JAPANESE MIXED-MODE OFFICE BUILDINGS

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ABSTRACT: This study investigates the overall comfort and productivity of Japanese office workers in mixed-mode office buildings. The indoor thermal environment is adjusted using the air-conditioning in Japanese office buildings to maintain thermal comfort and productivity. Thus, it is necessary to research thermal comfort and productivity to understand how occupants prepare themselves to be at a comfortable temperature and perform their daily tasks under mixed-mode (MM) and free-running (FR) modes. Environmental parameters such as air temperature, relative humidity, and so on were measured in 17 Japanese office buildings with the help of digital instruments, and thermal comfort transverse surveys were conducted for two years in Tokyo, Yokohama, and Odawara of Japan. The data were collected every once a month for a day visiting each building with the measurement instruments, together with the questionnaires. Almost 3000 votes were collected. This paper evaluates the overall comfort discussions followed by how the occupant could achieve their productivity. The occupants were found to be thermally comfortable and productive in the office. The most suitable comfortable temperature range for MM mode was found to be 22–26 °C and 23–25 °C for FR mode. The workers' productivity range is defined by the globe temperature range of 21–27 °C for MM and 20–27 °C for FR mode. The findings should be useful to suggest that whenever new office buildings are designed, these factors always need to be taken into consideration.

Keywords: Field Survey; Free Running Mode; Japanese office buildings; Mixed Mode; Productivity; Thermal Comfort.

التحقيق في الراحة الحرارية والإنتاجية في المباني المكتبية اليابانية المختلطة

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الملخص: تبحث هذه الدراسة في الراحة العامة والإنتاجية للعاملين في المكاتب اليابانية في مباني المكاتب ذات الوضع المختلط. يتم ضبط البيئة الحرارية الداخلية باستخدام تكييف الهواء في مباني المكاتب اليابانية للحفاظ على الراحة الحرارية والإنتاجية. وبالتالي، من الضروري إجراء بحث حول الراحة الحرارية والإنتاجية لفهم كيفية إعداد أصحاب المكاتب لأنفسهم ليكونوا في درجة حرارة مريحة وأداء مهامهم اليومية في الوضع المختلط (MM) ووضع التشغيل الحر (FR). تم قياس معايير البيئة مثل درجة حرارة الهواء والرطوبة النسبية وما إلى ذلك في 17 مبنى مكاتب يابانيًا بمساعدة الأدوات الرقمية ، وأجريت استطلاعات عرضية للراحة الحرارية لمدة عامين في طوكيو ويوكوهاما وأوداوارا في اليابان. تم جمع البيانات مرة واحدة شهريًا لمدة يوم لزيارة كل مبنى باستخدام أدوات القياس بالإضافة إلى الاستبيانات التي تم ملؤها لما يقارب 3000 مرة. تقيّم هذه الورقة مناقشات الراحة الشاملة متبوعة بكيفية تحقيق الموظف لإنتاجيته. تم العثور على شاغلي المكتب مرتاحين حرارياً ومنتجين في المكتب. تم العثور على أنسب نطاق درجة حرارة مريحة للوضع المختلط (MM) هو 22–26 درجة مئوية و 23–25 درجة مئوية لوضع التشغيل الحر (FR). يتم تحديد نطاق إنتاجية العمال من خلال نطاق درجة حرارة الكرة الأرضية من 21 إلى 27 درجة مئوية لـوضع التشغيل المختلط و 20–27 درجة مئوية لوضع التشغيل الحر. يمكن الاستفادة من نتائج هذه الدراسة لأخذها في عين الاعتبار عند تصميم مباني جديدة.

الكلمات المفتاحية: الدراسة الاستقصائية الميدانية؛ نمط التشغيل الحر؛ مباني المكاتب اليابانية؛ النمط المختلط؛ الإنتاجية؛ الراحة الحرارية.

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DOI:10.53540/tjer.vol19iss1pp63-72

1. INTRODUCTION

Thermal comfort is a person's perception of how they feel related to the air temperature, radiant temperature, relative humidity, and air movement of their surroundings. According to ASHRAE (2017), "thermal comfort is defined as the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation." The fact is that the relationship between the individual and the environment is very complex and active due to the presence of various factors like climate, buildings, social, economic, and some other factors. Today, people spend more and more time indoors, where they expect a level of thermal comfort that ensures comfort and wellbeing. Even gentle fluctuations can cause discomfort, which may lead to a sudden change in the behaviour or the activity of the occupant. Therefore, it is important to provide better working thermal environments, so-called "comfortable environments".

Japanese office buildings are well equipped with air-conditioning (AC) systems to help in creating thermal comfort. Although the Japanese office buildings do have AC systems, it seems that the various practices, such as opening doors and windows to allow air movement as much as possible, enable the occupants to be at their required thermal comfort while at work. The Japanese government introduced the "Cool Biz" and "Warm Biz" programs that recommend an indoor temperature of 28 °C for cooling and 20 °C for heating in the year 2005 (Enomoto *et al.*, 2009).

Productivity is defined as the extent to which activities result in the achievement of the system goals (Parsons 2003). Individuals always have different thermal expectations, which will differ from individual to individual. People have different thermal expectations, and thus thermal comfort is likely to vary according to the month, season, and mode. According to Seppanen *et al.* (2006), the productivity increases with air temperature up to 21–22 °C. They found that the highest productivity is achieved at an air temperature of around 22 °C. For example, at the air temperature of 30 °C, the productivity is only 91.1% of the maximum, i.e., the reduction in performance is 8.9%. Horr *et al.* (2016) reviewed a broad range of literature and found that many factors affect occupant comfort and productivity. Vimalanathan and Ramesh Babu (2014) investigated the significant effects of indoor room temperature and illumination on the office worker's performance. It was found that the suitable optimum level for indoor room temperature was 21°C.

An experimental study conducted by Ismail *et al.* (2014) found that along with temperature, illuminance and relative humidity also dominated the productivity of workers. Based on a review of existing literature by Fisk *et al.* (1997), there is strong evidence that characteristics of buildings and indoor environments significantly influence rates of workers' productivity.

The experimental results in Tsay *et al.*'s (2022) study showed that male and female workers have different optimal temperatures for their productivity at work. Rasheed *et al.* (2021) found that there were significant differences in perceptions of comfort and productivity for those who spent less time and those who spent more time at work. Ngarmpornprasert and Koetsinchai (2010) found a satisfactory thermal condition for office workers by maintaining the temperature at 26–28 °C for morning periods and 24.5–26 °C for afternoon and evening periods.

Based on field surveys, the comfort temperatures in Japanese offices have been investigated by several researchers (Rijal *et al.*, 2017). However, not much research has been conducted to investigate the relationship between thermal comfort and productivity in Japanese office buildings as compared to other countries. Comfortable temperatures are important to investigate because the indoor temperatures chosen affect the energy used in the building, and people in thermal comfort are generally more productive. Thermal discomfort caused by high or low air temperature had a negative influence on office workers' productivity, and the subjective rating scales were important supplements of neurobehavioral performance measures when evaluating the effects of indoor environmental quality on productivity (Lan *et al.*, 2012). However, most of the previous studies are conducted in summer, and thus thermal comfort for other seasons and in mixed-modes office buildings is still unknown.

The basic principles are largely universal, but thermal comfort varies from person to person. Therefore, long-term data are required to fully describe the occupants' perceptions and behavioural responses to the thermal environment in their offices (Rijal *et al.*, 2017). The more control over the thermal comfort, the better a person can feel and more productive at work they will become. According to Tanabe *et al.* (2007), evaluating the productivity of office workers promotes the effort for energy conservation. The short data collection periods and few samples' collections are also the major drawbacks of not having significant research on this topic so far.

We conducted a transverse survey to record the thermal comfort and productivity responses of the Japanese office workers. Furthermore, the responses were analyzed to determine the occupants' overall comfort and productivity under mixed-mode (MM) and free-running (FR) mode. This research holds 3000 votes from 17 different mixed-mode office buildings located in Tokyo, Yokohama, and Odawara and the data are collected for two years.

2. METHODOLOGY

2.1 Investigated areas and buildings

This field survey was carried out in 17 different office buildings located in Tokyo, Yokohama, and Odawara of Japan from August 2014 to October 2015 and from August 2017 to November 2018 (Fig. 1). Table 1 shows the description of the investigated buildings, including locations and investigated floors. The investigated buildings were of change-over mixed-mode types. The change-over mixed-mode buildings have openable windows and doors, or can be air-conditioning mode depending on the seasons or time of the day (CBE, 2021). The survey was carried out for two years to ensure collecting as much information as possible for different months and different seasons (Rijal *et al.*, 2019, 2022).

2.2 Thermal measurement survey

Indoor and outdoor environmental variables were measured, including air temperature, globe temperature, relative humidity, and air movement. They were collected at 1.1 m height above floor level, away from direct sunlight, using digital instruments as shown in Fig. 2. Climatic data were obtained from the nearest meteorological stations (Table 1). Table 2 shows the characteristics of the instruments used in the survey. A globe thermometer with a diameter of 75 mm or 40 mm rather than 150 mm is widely used for thermal comfort field surveys (Nicol *et al.*, 1994, de Dear *et al.* 1997, Nicol *et al.* 1999, Brager *et al.* 2004, Humphreys and Nicol 2007, Rijal *et al.*, 2019a). The time constant for the globe thermometer with the 150 mm diameter is about 20 minutes (Spagnolo and de Dear 2003, Rijal *et al.* 2003) but it is less for the globe thermometer with the diameter of 75 mm which would be sufficient to stabilize in the indoor space. Furthermore, the response time for temperature measurement in practical life is higher for smaller ones because of the smaller surface (Humphreys 1977, Nicol *et al.*, 2012). Recently, d'Ambrosio Alfano *et al.* (2021) found that the globe thermometer with a 50 mm diameter showed lower errors than 38 mm diameter. They also indicated that it is still unclear whether small globes, characterized by low response times, exhibit the same accuracy as the standard 150 mm in predicting the mean radiant temperature. The measured data was recorded 15–20 minutes after the instruments were set to ensure a stable measurement as shown in Rijal *et al.* (2017).

Figure 1. General view of one of the investigated office buildings in Yokohama.

Figure 2. Digital instrument set up (Rijal *et al.* 2017)

Table 1. Description of the investigated buildings

Building code	Location*	Investigated floor**
B2	Yokohama	1F, 3F~5F
B4	Yokohama	1F, 2F
B5	Yokohama	3F~7F
B6	Yokohama	1F
B7	Tokyo	1F, 4F
B8	Tokyo	1F, 2F
B13	Tokyo	2F~5F
B14	Tokyo	1F, 3F, 4F
B15	Tokyo	1F
B16	Tokyo	1F~3F
B17	Tokyo	1F
B18	Tokyo	2F,3F
B19	Tokyo	1F, 4F
B20	Tokyo	2F~4F
B21	Tokyo	4F
B22	Tokyo	4F
B23	Odawara	2F

*: Meteorological station, **: The floor is counted by the American system, F: Floor

Table 2. Description of the instruments used.

Parameter measured	Trade name	Range	Accuracy
Air temp., Humidity	TR-76Ui	0 to 55 °C, 10% to 95% RH	±0.5 °C, ±5%RH,
	Tr-52i	−60 to 155 °C	±0.3 °C
Globe temp.	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%

2.3 Thermal comfort and productivity survey

Each investigated building was visited for one day each month to collect the instruments' measurements and subjects' filled questionnaires. The reading was taken just once for each group on each visit to each office. The survey methods are given in Rijal *et al.* (2017). To collect the data, the instruments were planned and set up on the office table, and the questionnaires were distributed among the occupants seated near the instruments, as shown in Fig. 3. When people were filling up the questionnaire, the researcher recorded the common environmental controls and the physical data from them. After collecting the data for that group, the instruments were moved to the next group and, so on. This process was repeated every month. The data includes overall comfort and productivity.

Table 3 shows the scale used in the survey. We have used a six-point unidirectional scale as it is widely accepted for thermal comfort and productivity surveys (McCartney and Nicol, 2002). In particular, it provides more categories for the thermal comfort scale than the scale given in ISO (1995). The survey was carried out in the Japanese language. We have collected the data from the healthy office workers.

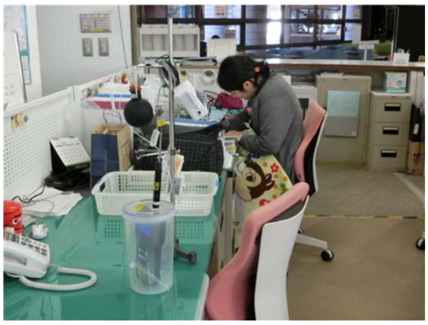


Figure 3. Thermal comfort and productivity survey (Rijal *et al.*, 2019).

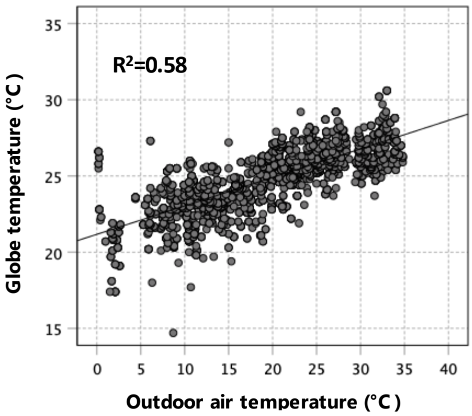
Table 3. Overall comfort and productivity scale.

Scale	Overall comfort	Productivity
1	Very uncomfortable	Very difficult to work
2	Moderately uncomfortable	Difficult to work
3	Slightly uncomfortable	Slightly difficult to work
4	Slightly comfortable	Slightly easy to work
5	Comfortable	Easy to work
6	Very comfortable	Very easy to work

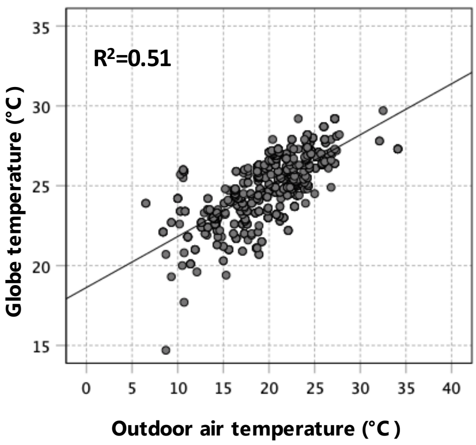
3. RESULTS AND DISCUSSION

3.1 Thermal environment during the survey

The relationship between the indoor and outdoor thermal environment was investigated by statistical analysis. It was found that the range of indoor globe temperature is similar to the indoor air temperature. Globe temperature is highly correlated with the indoor air temperature for mixed-mode (r = 0.76) and free-running mode (r = 0.71), so the globe temperature was used for further analysis. Moreover, the globe temperature measures the combined effects of radiant heat, air temperature, and wind speed. The mean indoor air temperature in MM was maintained at 22.8 °C during winter and 26.5 °C during summer. It is slightly close to the recommendation of the Japanese government that the indoor temperature is at 20 °C in winter and 28 °C in summer. The mean outdoor temperatures were 8.5 °C during winter and 28.0 °C during summer for MM conditions. Figure 4 shows the relationship between the indoor globe and the outdoor air temperatures for MM and FR modes. The mean globe temperature during the voting was 24.8 °C, 25.0 °C for the MM and FR, respectively. Although there is seasonal variation in the monthly outdoor temperature as shown in Table 4, the changes in the globe's temperature are quite small. A probable reason is that the workers used heating and cooling during winter and summer to maintain the working thermal environment in MM.



(a) MM



(b) FR

Figure 4. Relationship between the globe temperature and outdoor air temperature: (a) MM and (b) FR mode.

3.2 Overall comfort and productivity

3.2.1 Distribution of overall comfort

To investigate how office workers' perceive overall comfort under the environmental conditions (i.e. temperature, humidity, and air movement), the overall comfort votes were obtained from the questionnaires. Most of the occupants voted for "3. slightly comfortable", as shown in Figure 5. Very limited responses were obtained at "1. very uncomfortable", "2. moderately uncomfortable", and "6. very comfortable". The reasons might be that the MM created a comfortable indoor environment and thereby fewer responses at "1. very uncomfortable" and "2. moderately uncomfortable". As for FR mode, they may use clothing adjustment to feel comfortable. The mean overall comfort for the MM and FR was 3.91 and 3.99, as shown in Fig. 5. Both of them are very close to "4. slightly comfortable". This suggests that the occupants are comfortable with their thermal environment at the office building under both modes.

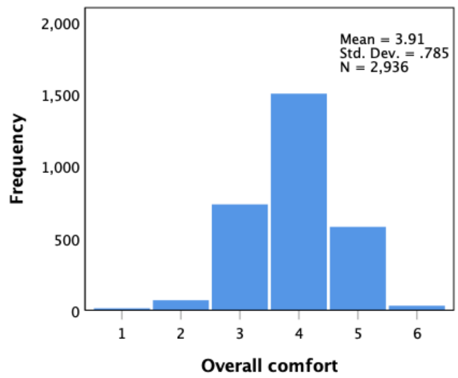
3.2.2 Distribution of productivity

The productivity responses were obtained by considering the air temperature, humidity, air movement, lighting, indoor air quality, and overall comfort. Figure 6 shows the distribution of productivity in MM and FR modes. The mean productivity for the MM and FR were 4.0 and 4.1. Most of the responses were at "4. slightly easy to work" and then at "5. easy to work" for both modes. Very limited responses were obtained at "6. very easy to work" in both modes.

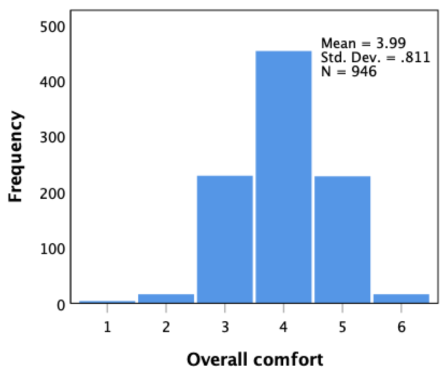
Table 4. Seasonal differences of outdoor temperature and globe temperature.

Mode	Description	Winter		Spring		Summer		Autumn		All	
		T_{out} (°C)	T_g (°C)	T_{out} (°C)	T_g (°C)	T_{out} (°C)	T_g (°C)	T_{out} (°C)	T_g (°C)	T_{out} (°C)	T_g (°C)
MM	N	680	680	579	579	848	848	839	837	2946	2944
	Mean	8.5	22.7	19.4	25.0	28.0	26.3	20.1	24.9	19.6	24.8
	S.D.	3.4	1.7	4.4	1.7	4.8	1.0	4.9	1.7	8.3	2.0
FR	N	45	45	313	313	153	153	438	436	949	947
	Mean	10.1	22.9	21.0	25.4	22.7	26.1	19.5	24.6	20.1	25.0
	S.D.	1.3	2.2	2.5	1.9	3.4	1.0	4.3	1.9	4.3	1.9

T_{out}: Outdoor air temperature, T_g: Globe temperature, N: Number of records, S.D.: Standard deviation.

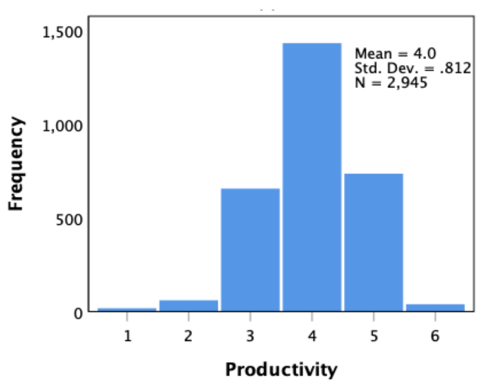


(a) MM

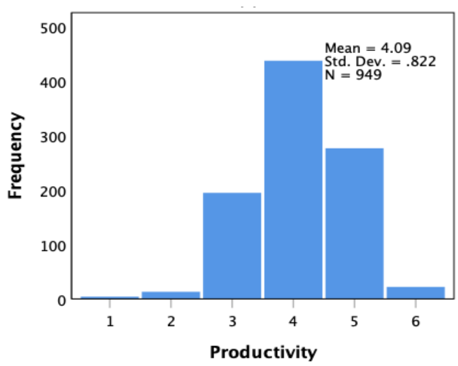


(b) FR

Figure 5. Distribution of overall comfort: (a) MM and (b) FR mode.



(a) MM



(b) FR

Figure 6. Distribution of productivity: (a) MM and (b) FR mode.

3.2.3 Relationship between overall comfort and productivity

Figure 7 shows the relationship between overall comfort and the productivity of the occupant. The results showed that the higher the overall comfort, the higher the productivity ($p<0.001$) in both MM and FR modes. A study by Leaman and Bordass (1999) report that comfort and perceived productivity is greater in buildings where occupants have more control over the environment and in MM buildings that have both natural ventilation and air conditioning.

Accordingly, further analysis was conducted to confirm the relationship between overall comfort and productivity responses with the globe temperature, which determines the comfortable temperature range for MM and FR modes.

3.3 Relation between overall comfort and globe temperature

Figures 8(a) and 8(b) show the relationship between overall comfort and globe temperature in the MM and FR modes. The majority of responses were within the temperature range of 20–28 °C in both modes. The regression equations obtained are shown in Table 5. To find the globe temperature, which corresponds to the peak value of overall comfort, it is necessary to estimate where the curve is horizontal (has a slope of zero). This can be found by equating the equation to zero and differentiating the quadratic equation concerning globe temperature.

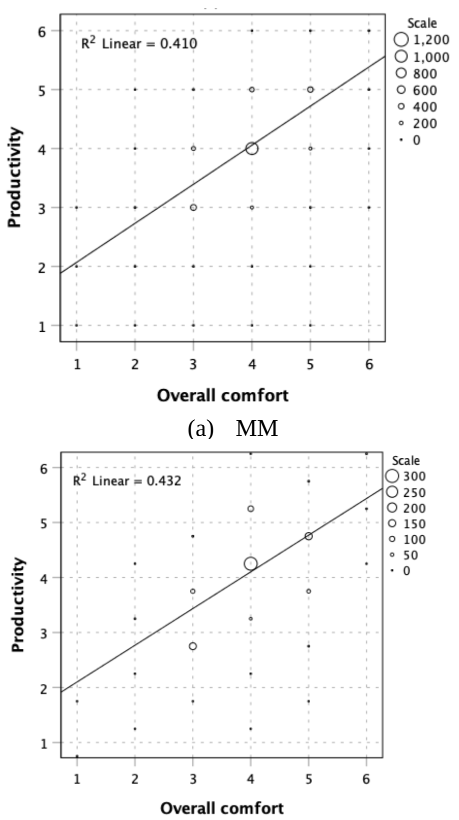


Figure 7. Relationship between overall comfort and productivity: (a) MM, and (b) FR mode.

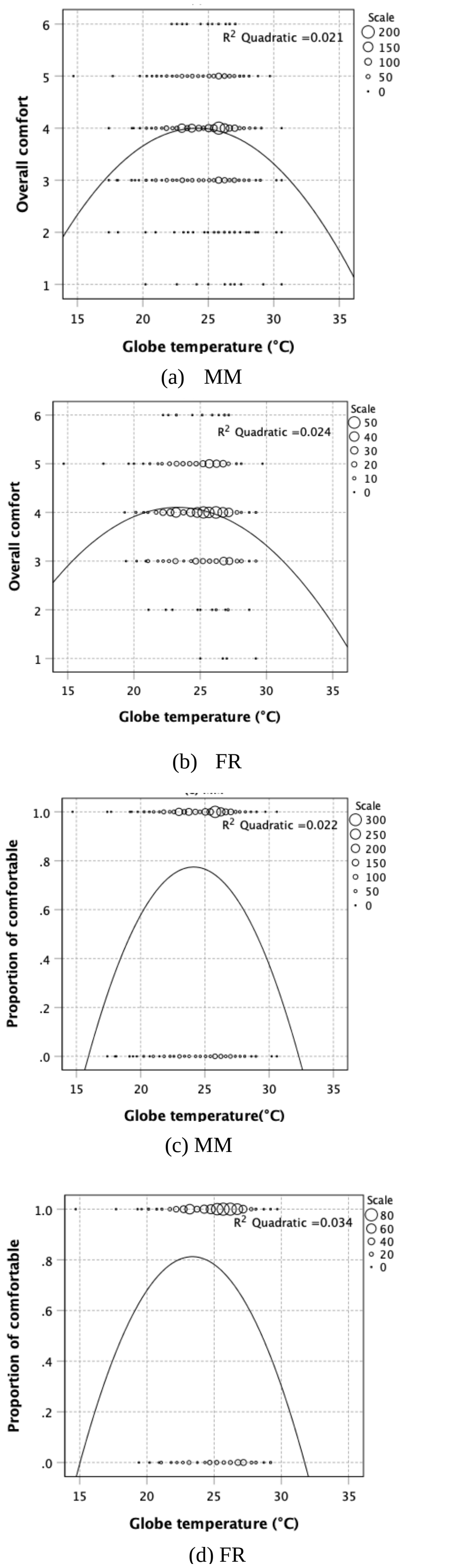


Figure 8. Relationship between overall comfort and globe temperature: (a) MM and (b) FR mode using raw data, and (c) MM and (d) FR mode using binary data.

The optimum globe temperatures for MM and FR modes are 24.0 °C and 20.3 °C, respectively. Beyond the optimum globe temperature, uncomfortable increases because of a decrease or increase in temperature.

The overall comfort scale was modified into binary form for the proportion of comfortable $P_{MM}(0,1)$ for MM mode and proportion of comfortable $P_{FR}(0,1)$ for FR mode. The scales of “1. very uncomfortable”, “2. moderately uncomfortable”, and “3. slightly uncomfortable” are classified as uncomfortable and codded by 0. The rest of the scales are classified as comfortable codded by 1. Figures 8 (c) and (d) show the quadratic regression analysis conducted between the binary overall comfort data and the globe temperature. The quadratic equations are as shown in Table 5.

At 0.8 proportion of comfort, the comfortable range is 22–26 °C for MM and 23–25 °C for FR mode. The derivatives of the equations give the optimum globe temperatures of 28.0 °C for MM and 27.0 °C for FR mode.

3.4 Relation between productivity and globe temperature

To identify the comfortable range for productivity, Figs. 9(a) and 9(b) show the regression analysis between productivity and the globe temperature. The quadratic regression equations are as shown in Table 6. The optimum globe temperatures for MM and FR modes are 24.3 °C and 23.1 °C. The optimum globe temperature is similar to the overall comfort case. Beyond the optimum globe temperature, productivity decreases because of a decrease or increase in temperature.

To calculate the temperature for a given proportion, the productivity scale was modified to binary form. The scales of “1. very difficult to work”, “2. difficult to work”, and “3. slightly difficult to work” are classified as nonproductive and codded as 0. The rest of the scales are classified as productive, codded as 1. Figures 9(c) and 9(d) show the quadratic regression analysis between the proportion of productivity and the globe temperature. The equations are shown in Table 6.

At 0.75 proportion of productive responses, the globe temperature ranges of 21–27 °C for MM and 20–27 °C for FR mode were obtained. Above or below the mentioned globe temperature, occupants feel slightly difficult to work. In FR mode, the temperature range is slightly wider than in MM. The derivatives of the equations give the optimum globe temperatures of 23.7 °C for MM and 25.0 °C for FR mode.

Table 7 compares the optimum temperature with those found in previous studies. In the field study, the globe temperature is considered to be close to the operative temperature (Nicol *et al.,* 1999, Humphreys *et al.*, 2013). According to our study, the indoor air temperature is close to the globe temperature. Based on this evidence, we made some possible comparisons. Even though the analyzing index temperatures are different in the previous studies, there are some similarities between them.

Table 5. Quadratic regression equations for overall comfort and globe temperature.

Mode	Equation	N	R^2	S.E.₁	S.E.₂	p
MM	$P_{MM} = -0.02T_g^2+0.96T_g -7.61$	2946	0.021	0.003	0.122	<0.001
FR	$P_{FR} =-0.02T_g^2+0.81T_g -5.37$	949	0.024	0.005	0.23	<0.001
MM(0,1)	$P_{MM} =-0.01T_g^2+0.56T_g -5.95$	2946	0.022	0.001	0.07	<0.001
FR(0,1)	$P_{FR} =-0.01T_g^2+0.54T_g -5.55$	949	0.034	0.003	0.13	<0.001

N: Number of responses, R^2: Coefficient of determination, $S.E._1$ and $S.E._2$: Standard errors of the regression coefficient of T_g^2 and T_g, p: Significance level of the regression coefficient.

Table 6. Quadratic regression equations for productivity and globe temperature.

Mode	Equation	N	R^2	$S.E._1$	$S.E._2$	p
MM	$P_{MM} = -0.015\ T_g^2+0.729T_g\ -4.55$	2946	0.013	0.003	0.127	<0.001
FR	$P_{FR} = -0.015\ T_g^2+0.693T_g\ -3.85$	949	0.018	0.005	0.236	0.002
MM(0,1)	$P_{MM} = -0.0082\ T_g^2+0.39T_g\ -3.86$	2946	0.013	0.001	0.07	<0.001
FR(0,1)	$P_{FR} = -0.009\ T_g^2+0.45T_g\ -4.53$	949	0.020	0.002	0.12	<0.001

N: Number of responses, R^2: Coefficient of determination, $S.E._1$ and $S.E._2$: Standard errors of the regression coefficient of T_g^2 and T_g, p: Significance level of regression coefficient.

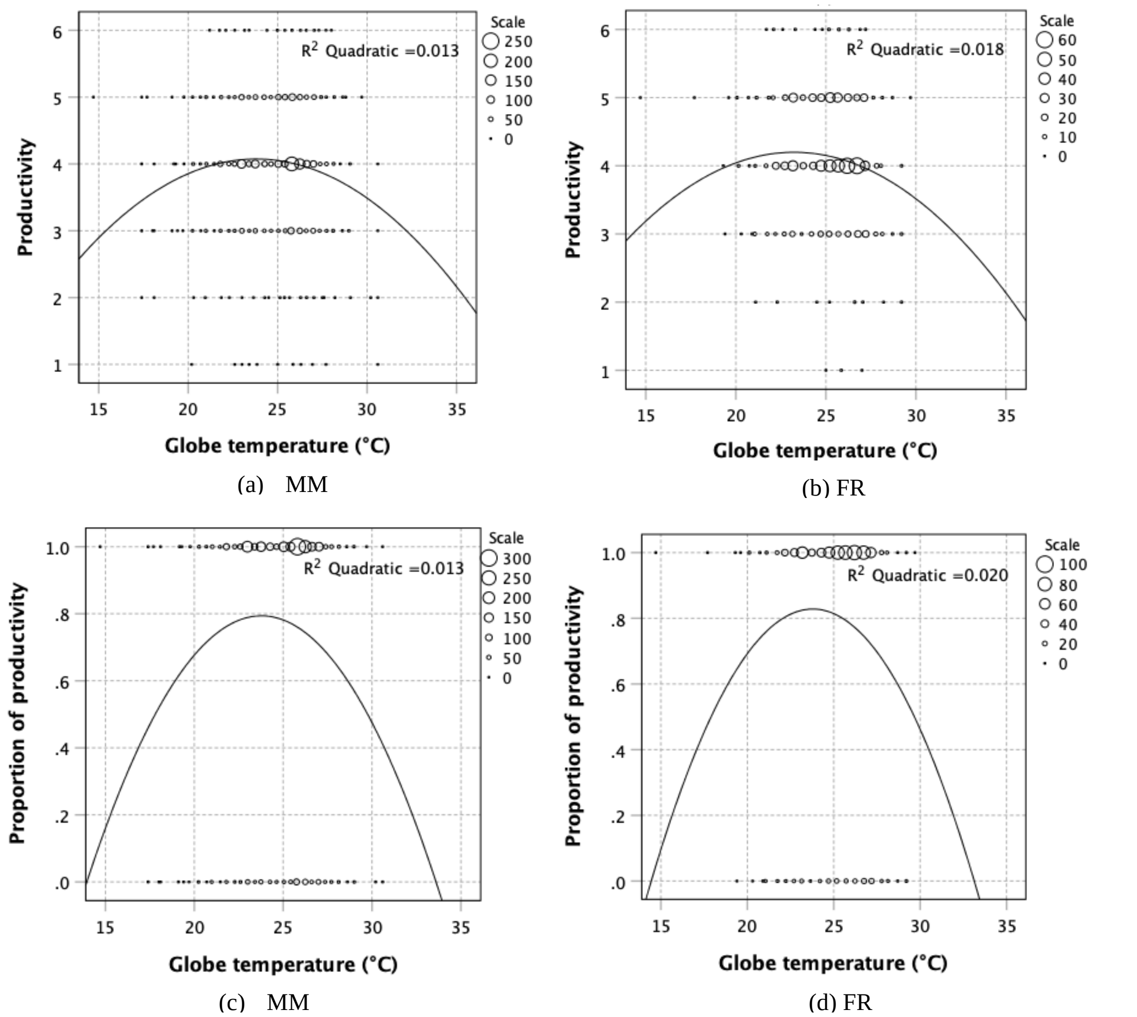


Figure 9. Relationship between productivity and globe temperature: (a) MM and (b) FR mode using raw data, and (c) MM and (d) FR mode using binary data.

Table 7. Comparison of optimum productivity temperature with previous studies

References	Country	Building type	Method	Index temperature (°C)	Optimum temperature for productivity (°C)
This study	Japan	MM	Field	T_g	MM: 24 FR: 23 MM range: 22–26 FR range: 22–25
Seppänen *et al.* 2006			Literature Review	T_i	21–22
Vimalanathan & Ramesh Babu 2014	India	MV	Field	T_i	21
Tanabe *et al.* 2013	Japan	MV	Field	T_{op}	Below 27
Ismail *et al.* 2014	Malaysia	MV	Climate chamber	T_{WBGT}	24
Tsay *et al.* 2022	Taiwan (ROC)	MV	Climate chamber	T_i	27(Male), 25 (Female)

T_g : Globe temperature, T_i: Indoor air temperature, T_{op}: Operative temperature, T_{WBGT}: Wet bulb globe temperature, MV: Mechanically Ventilated.

4. CONCLUSION

The thermal comfort survey was conducted for two years in Tokyo, Yokohama, and Odawara of Japan. The study evaluated the overall comfort and productivity of the Japanese office workers both qualitatively and quantitatively by using the responses and measuring indoor globe temperature. The following results were found.

1. The indoor globe temperature ± standard deviation is maintained at 24.8±2.0 °C in MM. Therefore, the fluctuation of the indoor globe temperature was small.
2. The analysis showed that the occupants were highly comfortable and productive in the indoor thermal environment of the office buildings.
3. The productivity increases with increasing the overall comfort and vice-versa.
4. The most suitable comfortable temperature range was found to be 22–26 °C for MM and 23–25 °C for FR mode. The workers' productivity range is defined by the globe temperature range of 21–27 °C for MM and 20–27 °C for FR mode. This suggests that whenever new office buildings are designed, these factors always needed to be taken into consideration.

ACKNOWLEDGEMENT

We are grateful to all those who participated in the survey, and to the students who helped with the data entry. We also thank the following organizations for their cooperation: Gotoh Educational Corporation, Hulic Co. Ltd., Nikken Sekkei Ltd., IDEA Consultants Inc., IS Logistic, Panasonic Corporation, PS Company Ltd., Tokyo City University, Tokyo City University Todoroki Junior and Senior High School, Tokyu Fudosan Next Generation Engineering Center Inc. and Tsuzuki Ward.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

FUNDING

This research was supported by Grant-in-Aid for Scientific Research (B) Number 21H01496.

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