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Experimental Study on Thermal Comfort Towards Increasing Temperature Set-Points in Air-Conditioned Office Spaces in a Tropical Region:

A Case Study in Thailand

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ABSTRACT

Many countries propose indoor temperature set-points of air-conditioned offices to be comfortably sustainable and to reduce energy consumption. Even though there are recommendations for the optimum temperature-set-points, it is questionable how those values could be applied to the actual situation in a tropical region. This study aims to survey thermal performance and estimate thermal comfort in different set-points. In 2019, two air-conditioned office buildings were tested by increasing set-points from the actual value between 23 °C and 25 °C. Data loggers measuring thermal variables were installed in the offices and the questionnaire was distributed to evaluate human response. Considering the ASHRAE psychometric chart, thermal environments of both cases on the day of a normal set-point were low; falling inside in the 1.0 clo zone. Thermal environments gradually moved from the 1.0 clo zone to the 0.5 clo zone, however, some of them were out of both comfort zones due to high absolute humidity. The predicted mean vote (PMV) and the thermal sensation vote (TSV) show that the votes changed from the cold side to the neutral side, and the higher acceptance rate was at warmer temperatures. The comfort temperature calculated from Griffith's method was found to be 23.6–25.1 °C which was lower than the measured operative temperature. Adaptive clothing behavior is described to confirm a better condition at warmer temperatures. A possibility of increasing cooling set-points at 24–25 °C is applicable to office buildings in the tropics to remain comfortable.

Keywords: *thermal comfort, air-conditioned, temperature set-point, office spaces, tropical region*

INTRODUCTION

Because of the threat of global warming, many countries are seeking solutions to reduce the emission of greenhouse gas produced from energy use (Houghton, 2009). The concept of controlling the optimum temperature set-points in the building was presented internationally to promote energy saving (Tan, 2008). Increasing the temperature set-point by just one degree Celsius could generate a 6% saving in energy consumption of air-conditioning systems (Kongkiatumpai, 1999). In the UK, the temperature set-point is concerned by the British Council for Offices which suggests that the value should be warmer than 22 °C in summer for energy saving and comfort (BCO, 2010). The experimental study in London proves that there is a possibility of changing a set-point from 22 °C to 24 °C without an increase of discomfort (Lakeridou, Ucci, Marmot, & Ridley, 2012). In Japan, the government launched a “Cool Biz” campaign in 2005 that promoted people to wear loose-fitting clothes so that they continued to stay at the cooling set-point up to 28 °C in summer (Nakashima, 2013). This campaign provokes awareness of better living conditions in the optimum indoor thermal environment. In a tropical region, outdoor temperature and relative humidity are constantly high throughout the year. Cooling indoor environment needs to use a large energy consumption to maintain human comfort (Yamtraipat, Khedari, & Hirunlabh, 2005). In Singapore, the official regulation, SS 554 (S.P.R.I.N.G, 2016), is applied to air-conditioning performance to limit the room temperature between 24 °C and 26 °C. The government of Malaysia (Lau, Tan, Lee, & Mohamed, 2009) suggests that the acceptable temperature should be at least 24 °C to reduce cooling energy demand without sacrificing comfort. In Thailand, the government tries to promote a 25 °C set-point in the peak of summer to reduce electricity bills (Energy Policy and Planning Office (EPPO), 2018). To produce efficiency of air-conditioning systems to match with human thermal comfort, HVAC systems have continuously developed, i.e., a chilled beam system or a radiant cooling system that provides suitable thermal physiology (De Dear & Brager, 1998). Currently, an air-conditioning system that is typical to be used for large-scale offices is a water-cooled chiller system. A chilled beam system is an air-conditioning type that is rarely used for office buildings in the tropics due to the sensitive humification from outdoor environments (Yang et al., 2019). The study in the US found that the performance of an active chilled beam system used with a 100% dedicated outdoor air system in parallel might result in significant relative energy savings providing up to 12% for the office in hot and humid climates (Kim, Tzempelikos, & Braun, 2019). However, the recommended values tend to be used in a holistic approach. Thermal comfort could be more flexible depending on several factors, such as the type of occupants (Sattayakorn, Ichinose, & Sasaki, 2017), ages and genders (Indraganti, Ooka, & Rijal, 2015), air-conditioning systems (Kim et al., 2019), etc.

The climate characteristics of a tropical region result in the high outdoor temperature ranging between 20 °C and 34 °C when the outdoor humidity is generally 77–88% in summer (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006). To maintain the cooling environment, the air-conditioning system of large commercial buildings in this region consumes over half of the electrical energy use (59.09%) (Yamtraipat, Khedari, Hirunlabh, & Kunchornrat, 2006). It becomes more severe when cooling loads may increase to 200 GW of extra generation capacity in 2040, predicted by the International Energy Agency (IEA, 2019). The relative humidity is the main factor that is critically concerned when mechanical engineers design the air-conditioning system (ASHRAE, 2017). To reduce humidity levels, cooling loads from the air handling unit (AHU) are sometimes provided lower than the design (Mathews, Botha, Arndt, & Malan, 2001). The study of Foo and Poon argues that there was 60% of office staff experiencing indoor temperature under 24 °C (Foo & Phoon, 1987). The neutral temperature of occupants in the air-conditioned offices is found to be 26.4 °C in Singapore, 25.6 °C in Malaysia, and 26.4 °C in Indonesia (Damiati, Zaki, Rijal, & Wonorahardjo, 2016). It reports a similar situation in other offices in the tropics that indoor temperature was mostly overcooled throughout the year (Sekhar, 2016). Bangkok, Thailand is one of the biggest cities in South East Asian that has a critical issue of high temperature and humidity (Yamtraipat et al., 2005). Regarding the Köppen climate classification, Bangkok, Thailand is identified as a hot and humid region in the AW zone (typical savanna) at 13° 02’ 19.93” N Latitude and 101° 29’ 24.37” E Longitude (Kottek et al., 2006). Due to the growth of office spaces in the country (CBRE, 2019), the indoor environment is given priority when people spend most of the time inside office buildings (United & Bureau of Labor, 2003). Some field studies showed that air-conditioned offices observed in Thailand fulfill thermal comfort criteria (Busch, 1992; Yamtraipat et al., 2006). However, the recommendations from those results are used for all building types or spaces. There is only a little evidence of open offices with a central air-conditioning unit investigated.

The awareness of thermal comfort is one of the criteria to obtain the well-known green building certifications around the world (Analytics, 2018). The green building accreditation organized by the World Green Building Council (WGBC) claims that indoor air quality is the major feature to be qualified (WGBC, 2018) while the International WELL Building Institute (IWBI) employs thermal comfort for long-term assessment of health and wellbeing aspects (IWBI, 2019). Sick building syndromes caused by poor indoor air quality could be solved by both passive and active design (CIBSE, 2006). Several building-related symptoms normally occur when temperature or humidity is uncontrolled (Amin, Akasah, & Razzaly, 2015). Indoor thermal environments that perform too cold temperatures or too high humidity strongly affect people in terms of physical health and mental health in the long run (Al horr et al., 2016). The study from the US found that setting room temperature higher than 23 °C is associated with a decrease in symptom reports (Mendell & Mirer, 2009). In air-conditioned offices, thermal environments may fit into the comfort zone, however, comfort does not always refer to be healthy because staying in an air-conditioning environment for the long term could make their bodies weak (Tham & Ullah, 1993). It is supportive of warm thermal performance to encourage a better health condition.

Based on the above-mentioned background, this study aims to survey the thermal performance of offices in a tropical region and to find the possibility and the obstacle of adjusting room temperature set-points to warmer values. It would be beneficial to the air-conditioned offices to improve building operating performance in order not only to save energy consumption but also to enhance satisfaction and health.

METHODOLOGIES

To understand the actual thermal performance of office spaces in the tropics, two fully air-conditioned offices in Bangkok Metropolitan, Thailand, were selected to be case studies. The surveys were in May and September 2019. We selected the newly-constructed office buildings regarding the heating, ventilation, and air conditioning (HVAC) system that represents the typical indoor environment in Thailand. Office A is a commercial office occupied by a single private company that was opened in 2017. Working spaces are located in the east and the west with a high-performance façade. The measurement area covers about 46% of the total floor area. The air-conditioning system of Office A is a typical water-cooled chiller system in which the system operation usually starts half an hour before working time at 8:00. Office B belongs to a government sector that opened in the mid of 2019. The working areas face the south and the southwest. The distance approximately 1.8–2.0 m from the envelop is used for circulation spaces to keep people away from the heat from outside. The air-conditioning system of Office B is an active chilled beam system in which the system operation usually starts from 6:30. The cellular executive rooms located in the inner area are excluded from this study. There are thermostat displays showing temperature and humidity to occupants only in Office B. We installed 10 measuring devices (Point A to Point J) in all office spaces referring to the thermal environments of each person sitting nearby. Table 1 describes the information of both investigated offices.

To understand thermal environments of the case studies, we used automatic-record data loggers to collect them which are listed in Table 2. The room temperature and the relative humidity were measured by the devices set at a height of 1.1 m close to the occupants at the interior zone and the perimeter zone. There were 10 sets of measuring devices recording thermal variables at 1-minute intervals, namely A–J, respectively. An anemometer was also set on a tripod to measure the wind velocity near the reference data logger points every 60 seconds in each location. This study is the blind test of adjusting the temperature set-points ranging from 23 °C to 25 °C. The limitation of 2 °C higher than the actual value depends on permission from the authorities. Additionally, CIBSE suggests that the operative temperature should not vary higher than 1 °C from the previous day to avoid severe discomfort (CIBSE, 2006). The temperature set-point was controlled by the Building Management System (BMS) from the facility management section. In this study, we only focus on increasing temperatures to see the effect of this factor on other variables. Even if temperature is not only one factor that causes human comfort, people easily perceived it at first. It is useful to understand all thermal behaviors based on different temperatures. Therefore, we did not adjust other variables, including relative humidity, ventilation flow, and wind speed. Outdoor temperature and outdoor relative humidity were obtained from the online database (Underground, 2019).

Table 1: Building Information

Building Code	**A**	**B**
General Information		
Period of investigation	22nd – 24th May 2019	9 – 11th September 2019
Owner	Private	Government
Opening year	2017	2019
Gross area (m^2)	56,000	22,000
Number of floors	25	20
Measuring floor details		
Floor level	11	7
Typical area (m^2)	1,400	1,022
Measuring area (m^2)	674	576
Office orientation	East, West	South, Southwest
Number of measuring points	10	10
Points in the perimeter zone	A, B, C, and J	A, B, C, and J
Points in the interior zone	D, E, F, G, H, and I	D, E, F, G, H, and I
Floor to floor (m)	4.2	4.0
Floor to ceiling (m)	3.2	3.0
Façade type	Laminated insulated glass	Laminated insulated glass
HVAC		
System type	Water-cooled chiller	Chilled beam
Cooling set-point (°C)	23	23
Period of operation	8:00–18:00	6:30–16:45

To understand the perception of occupants towards thermal environments, the questionnaire distributed to all occupants in the offices addressed the following details: 1) personal information, which was about gender, age, health condition; 2) clothing insulation, which was separated into 3 parts, including upper part, lower part, and shoes; 3) a 7-scale thermal sensation vote (TSV); 4) a 5-scale thermal comfort vote (TCV); a 5-scale thermal preference vote (TPV); and a 2-scale thermal acceptance vote (TAV). The total number of subjects was 110 persons (36 males and 74 females) from Office A and 78 persons from Office B (45 males and 33 females). Occupants answered the questionnaire twice a day in the morning and the afternoon (at 11:00 and 15:00) which were completely counted as 787 votes in total. A type of work is a computer-based task which that of Office A is related to human resource management while that of Office B is about policy planning. We informed occupants to avoid answering the questionnaire at the time when they left their seats or when they had a meeting.

Table 2: Measuring Devices and Methods

IEQ parameters	Measuring devices	Record interval
Air temperature/ Humidity/ Illuminance	TR-74Uvi	10 min
Mean radiant temperature (T_{mrt})	RTR-52A 7" Globe	10 min
CO2 concentration	TR-76Ui	10 min
Air Speed	Anemometer	60 sec

Table 3: Scale for the Subjective Questionnaire

Scale	Thermal sensation vote (TSV)	Thermal comfort vote (TCV)	Thermal acceptance vote (TAV)	Thermal preference vote (TPV)
-3	Cold			
-2	Slightly cold	Uncomfortable		Colder
-1	Cool	Slightly uncomfortable		Slightly colder
0	Neutral	Neutral	Acceptable	No change
1	Warm	Slightly comfortable	Unacceptable	Slightly warmer
2	Slightly hot	Comfortable		Warmer
3	Hot			

For the calculation, the mean radiant temperature is estimated by using the equation from ISO 7726 (ISO, 1998) for a standard globe of 0.15 m, MRT = $((GT_a+273)^4 + 2.5 \times 10^8 \times V_a^{0.6} (T_g - T_a)^{1/4} - 273)$, where T_a = air temperature, T_g = globe temperature, and v_a = wind velocity. The PMV calculation is used to estimate the data considering 1) thermal items that we measured during working hours, including temperature, relative humidity, wind velocity, 2) occupant's data; metabolic rate and clothing insulation. The value of metabolic rate is counted as 1.1 met according to a typical rate for occupants in the office written in ASHRAE 55 (ASHRAE, 2017). Clothing insulation rate is estimated from questionnaires applying the equation from ISO 9920 (ISO, 2007); $Icl = 0.161+0.835 \times \Sigma Iclu$, where Iclu is the effective thermal insulation according to the table of the insulation values of typical clothing ensembles. The operative temperature is used to compare the results with subjective votes calculated by $t_o = t_a + (1\text{-}A)(t_r - t_a)$, where t_o is the operative temperature, t_a is air temperature, and A is the coefficient related to air velocity (A = 0.5 when air velocity is ≤ 0.2 m/s). This study also considers the Predicted Mean Vote (PMV) which is a well-known calculation by using the results from thermal variables (room temperature, mean radiant temperature, humidity, and wind velocity) and human factors (metabolic rate and clothing insulation) (Fanger, 1970). This model is widely used to estimate thermal sensation which the recommended value ranges from -0.5 to 0.5 when the metabolic rate of occupants is 1.0–1.3 met. We use this model to realize how much thermal environments would suit the recommended zone.

RESULTS AND DISCUSSION

As the results, the average room temperature and the average relative humidity were reading from 8:00 to 17:00 illustrated in Figure 1. The measuring Point A, B, C, and J were defined as the perimeter zone while measuring Point D, E, F, G, H, and I were defined as the interior zone. On the first day (set-point = 23 °C), the average room temperature of Office A started from 24.1 °C which was 1.1 °C higher than the set-point. The value reached 23.5 °C at 11:00 and it was stable around 23.7 °C until 17:00. There was only 14% of it dropping below 23 °C. Point C in the perimeter zone tended to be the most critical point when the temperature reached the highest value at 25.4 °C or +1.4 °C higher than the set-point. The average room temperature in Office B also started from 24.1 °C and began to be cooler at 23.2 °C nearly to the average of temperature in Office A. The main reason of the warm temperature in the morning was about the air-conditioning system that just began to operate on Monday after the weekend. Although the condition on Monday led higher temperatures than the set-point, there was 34% of the values dropping below 23 °C, especially at Point E and H, where the minimum value was 21.1–21.7 °C. The room temperature on the actual set-point day in Office A was less stable than that in Office B because of a small temperature gap. On the second day (set-point = 24 °C), the average temperature in Office A shifted from that on the first day by +0.1 °C on the average (23.6 °C). It increased

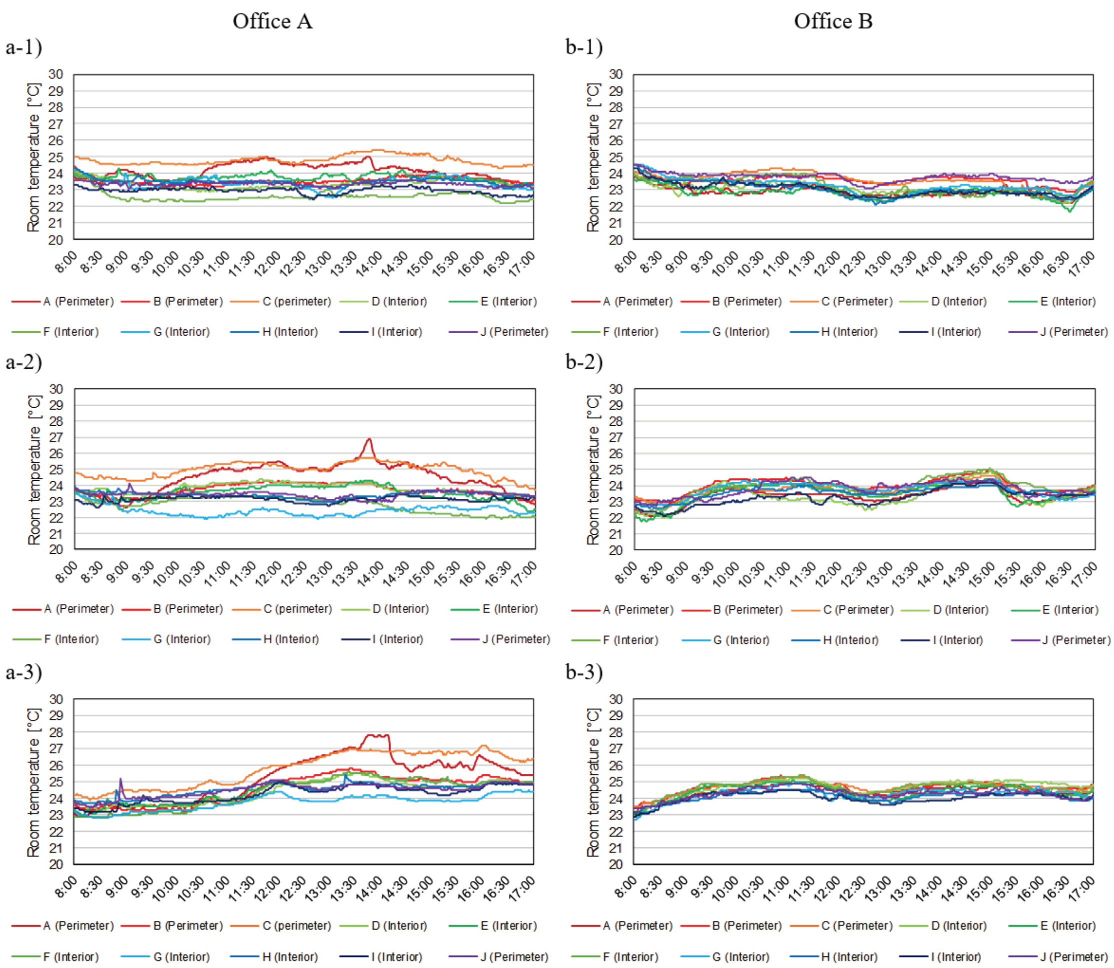


Figure 1:
Room temperature of case studies a-1) Office A at set-point 23°C, a-2) Office A at set-point 24°C, a-3) Office A at set-point 25°C, b-1) Office B at set-point 23°C, b-2) Office B at set-point 24°C, b-3) Office A at set-point 25°C

during the afternoon, particularly that at Point A and C, which was different from the mean by +0.9 °C and +1.4 °C, respectively. In contrast, the room temperature at Point G in the interior zone went lower than 24 °C dropping to 21 °C in the afternoon. High fluctuation depended on the cooling performance of air outlets when the set-point was changed. The temperature in Office B was 23.6 °C on average decreasing 0.6 °C cooler than the set-point. A temperature gap between the perimeter zone and the interior zone was not significantly different due to the high heat protection of façade performance. The highest gap zone between a minimum and a maximum was shown at Point F in the interior zone (ΔT = 3 K). On the third day (set-point = 25 °C), Office A performed high fluctuations mainly at Point A and Point C in the afternoon which were different from the average by 3.2 °C. The heat gained at Point A and Point C facing the west when the cooling from air outlets was insufficient. The values at Point G remained low at 22.8 °C in the morning and at 23.8 °C in the afternoon while Point A showed the highest level in the afternoon at 27.8 °C (ΔT = 5K). There was 68% of the values in Office A falling under 25 °C. That in Office B remained stable throughout the day at all points which the average was 24.4 °C. The difference between the lowest and the highest was only 2.7 °C (22.7 °C at Point G in the interior zone and 25.4 °C at Point B in the perimeter zone). The recorded data declared that 90% of the points in Office B were still under 25 °C, and 49% of them were higher than 24.5 °C.

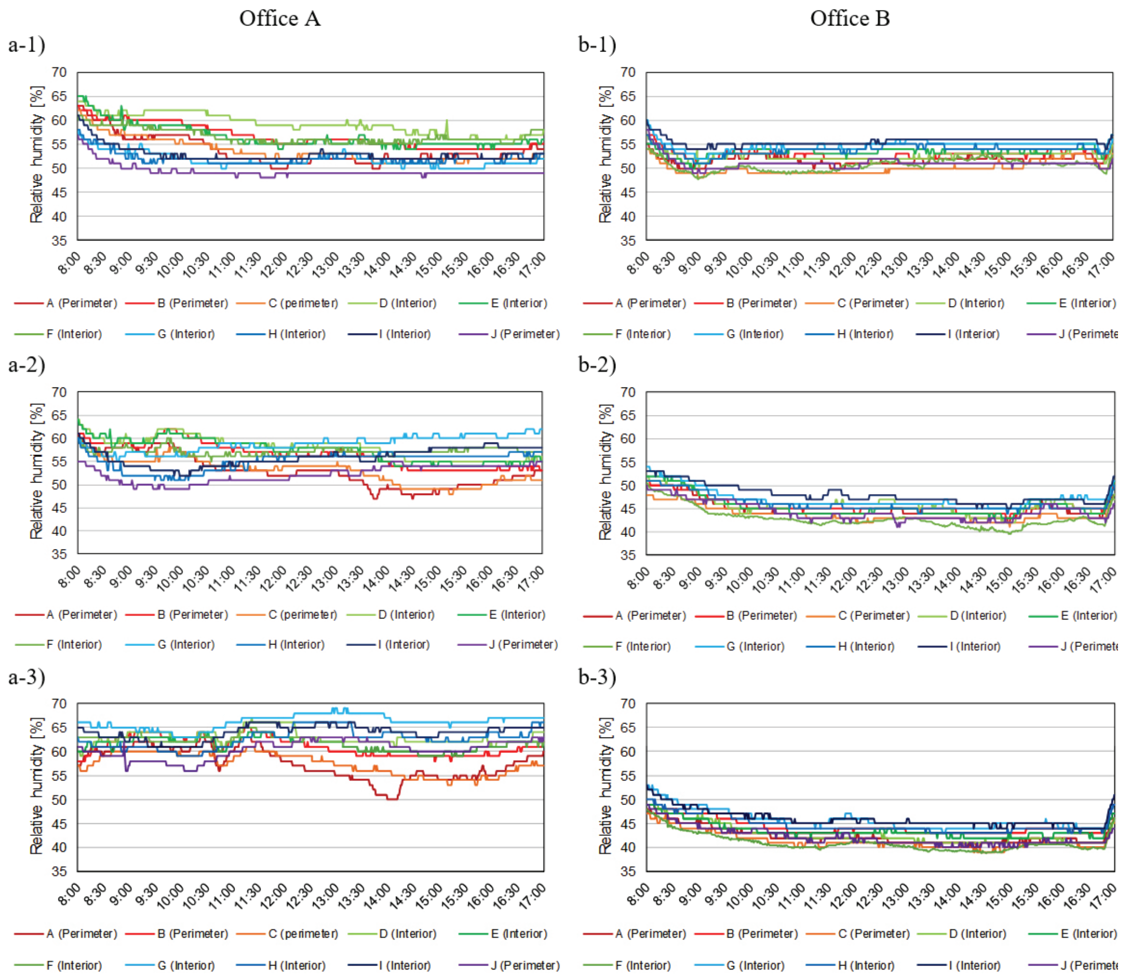


Figure 2:
Relative humidity of case studies a-1) Office A at set-point 23°C, a-2) Office A at set-point 24°C, a-3) Office A at set-point 25°C, b-1) Office B at set-point 23°C, b-2) Office B at set-point 24°C, b-3) Office A at set-point 25°C

Figure 2 shows the relative humidity from 8:00 to 17:00 in both offices. On the first day, the average relative humidity in Office A started at 60.9% before decreasing to 55.3% at 11:00 and it was ranging 54 – 56% during the day. The highest value was located at Point D in the interior zone at 59% when the lowest value was at Point J in the perimeter zone at 49%. On the other hand, the average relative humidity in Office B started at 57% and continued to be stable ranging as 50–56%. The highest average value was 56% at Point I in the interior zone while the lowest one was 50% at Point C in the perimeter zone. The humidity levels in both offices were in the optimum range (40–60%). On the second day, the results in Office A showed a similar tendency to those on the first day. The highest average value was at Point G in the interior zone at 59% and the lowest average value was at Point J in the perimeter zone at 52%. The values at Point A and B were dropped to 47% in the afternoon relevant to the highest room temperature at 26.9 °C. In Office B, the value slightly dropped to 45% and was constant throughout the day. On the third day, the average in Office A reached 66% at Point G which was over the recommendation of the ASHRAE standard, while the lowest value at Point C went below 57%. The difference of RH in Office A was about 20 when the average in Office B was still well controlled at 43% during the day. The excessive humidity could happen in a conventional air-conditioning system when it could reduce humidity from outside in time. This evidence is correlated with office cases in Singapore (Tham & Ullah, 1993) that the air-conditioning system is normally concerned with the indoor relative humidity which the value should not be over 70%. It requires to remove water vapor from the intake air and lead a high lantern heat load. The airflow through the cooling coil condenses immoderate moisture.

Table 4 describes the results of collected thermal variables. It is advantageous to compare those values by finding the correlation between each thermal index. We measured several temperature indices in order to confirm that the building is well-insulated so that we could increase temperature set-points with less effect of the heat near the perimeter zone. Trendlines of those indices could be different when the insulation of the envelop is insufficient, for example, glass window types that could not protect the heat radiation from outside (Damiati et al., 2016). Since the trendlines are almost diagonal as shown in Figure 3, we could use all temperature indices for the estimation. However, this study mainly uses the operative temperature to define thermal comfort compare with subjective votes. Changing temperature set-points does not affect other thermal indices such as outdoor temperature and outdoor humidity. According to the online data (Underground, 2019), the outdoor weather during the survey was mostly sunny but sometimes it was partly cloudy. The average outdoor temperature of Office A was 30.8–31.6 °C with 63.2–68.9% RH, respectively. That of Office B was constant at 31.3–31.6 °C with 63.2–68.9% RH. The temperature difference between indoor and outdoor was quite stable at 6.7–8 °C. Wind velocity was not significantly different which the average was 0.06–0.1 m/s. This rate was a normal condition on air-conditioned offices in the tropics. In addition, there is a study of thermal comfort in a hot-mid condition in Japan referring that increasing air velocity up to 0.2 m/s would be beneficial to the building in the tropic with lower energy consumption (Tanabe & Kimura, 1994). However, to emphasize on a temperature factor, this study did not set wind speed.

Thermal environments were plotted on the ASHRAE psychometric chart by using the operative temperature against the absolute humidity. Figure 4 defines 2 comfort zones; 1) the 1.0 clo comfort zone which fits to people who wear suits and ties or sweaters, 2) the 0.5 clo comfort zone which is recommended to people who wear light shirts like those in the tropics normally wear. Thermal environments of Office A slightly shifted from the 1.0 clo zone to the 0.5 clo zone as 20%, 25%, and 54% respectively, while those of Office B progressively changed to the recommended zone by 6%, 21%, and 82%, respectively. Most values of Office B on the last day fell inside the recommended zone with the highest rate. In contrast, those in Office A on the third day moved out from the comfort zone at 42% when absolute humidity reached over 0.012 g/g (DA). The main reason is humidification of a water-cooled chiller system might not effectively reduce humidity in time.

To find the aspect of occupants experiencing thermal variables, the study declares the subjective votes of each experimental set-point. The thermal sensation votes (TSV) illustrated in Figure 5 shows that most occupants in both cases felt neutral in every day of the survey. The average TSV changed from negative values to positive values which that of Office A was -0.6, -0.3, and 0.6, while that of Office B was -1, -0.4, and 0, respectively. TSV was classified into 3 categories; a colder-than-neutral group (TSV = -3, -2, and -1 or TSV-), a warmer-than neutral group (TSV = 1, 2, and 3 or TSV+), and a neutral group (TSV = 0). In Office A, the ratio of these three groups was

Table 4: Thermal variables of case studies

Set-point (°C)		T_r (°C)	T_g (°C)	T_{mrt} (°C)	T_{op} (°C)	RH (%)	AH (g/g(D/A))	AV (m/s)	T_{out} (°C)	RH_{out} (%)
A										
23	Min	22.2	21.7	21.0	21.8	48.0	0.009	0.04	27.2	52.0
	Max	25.4	25.2	25.4	25.2	65.0	0.012	0.21	33.9	89.0
	Mean	23.5	23.5	23.4	23.5	54.2	0.010	0.10	30.8	63.2
	SD	0.6	0.7	0.9	0.7	3.4	0.001	0.04	2.4	11.0
24	Min	21.9	21.6	21.4	21.6	47.0	0.009	0.03	27.2	59.0
	Max	26.9	26.7	27.5	26.7	64.0	0.012	0.12	33.9	89.0
	Mean	23.6	23.6	23.7	23.6	55.7	0.010	0.07	31.6	68.9
	SD	0.8	0.9	1.0	0.9	3.1	0.001	0.03	2.1	9.1
25	Min	22.8	22.7	22.5	22.7	50.0	0.010	0.02	27.8	52.0
	Max	27.8	28.0	28.2	28.0	69.0	0.013	0.20	33.9	89.0
	Mean	24.6	24.6	24.6	24.6	61.5	0.012	0.07	31.3	63.2
	SD	1.0	0.9	1.0	0.9	3.2	0.001	0.05	1.8	11.0
B										
23	Min	21.7	21.4	20.7	21.4	41.7	0.0088	0.03	27.8	55.0
	Max	24.5	24.9	25.7	24.9	60.0	0.0117	0.16	32.8	79.0
	Mean	23.2	23.2	23.2	23.2	52.7	0.0095	0.09	31.5	62.2
	SD	0.5	0.6	0.8	0.6	2.0	0.0004	0.04	1.6	7.1
24	Min	21.8	21.5	20.8	21.6	39.5	0.0077	0.04	28.9	59.0
	Max	25.1	25.1	25.32	25.1	54.0	0.0096	0.017	32.8	74.0
	Mean	23.6	23.6	23.6	23.6	45.4	0.0084	0.08	31.6	64.8
	SD	0.6	24.4	0.7	0.6	2.4	0.0003	0.04	1.4	4.3
25	Min	22.7	22.6	22.5	22.6	38.8	0.0076	0.03	27.8	52.0
	Max	25.4	25.6	25.9	25.6	53.0	0.0097	0.10	33.9	89.0
	Mean	24.4	24.4	24.4	24.4	43.4	0.0084	0.06	31.3	63.2
	SD	0.4	0.5	0.6	0.5	2.4	0.0004	0.02	1.8	11.0

Note: T_r: Room temperature; T_{mrt}: Mean radiant temperature; T_{op}: Operative temperature; RH: Relative humidity; AH: Absolute humidity; AV: Air velocity; T_{out}: Outdoor temperature; RH_{out}: Outdoor relative humidity

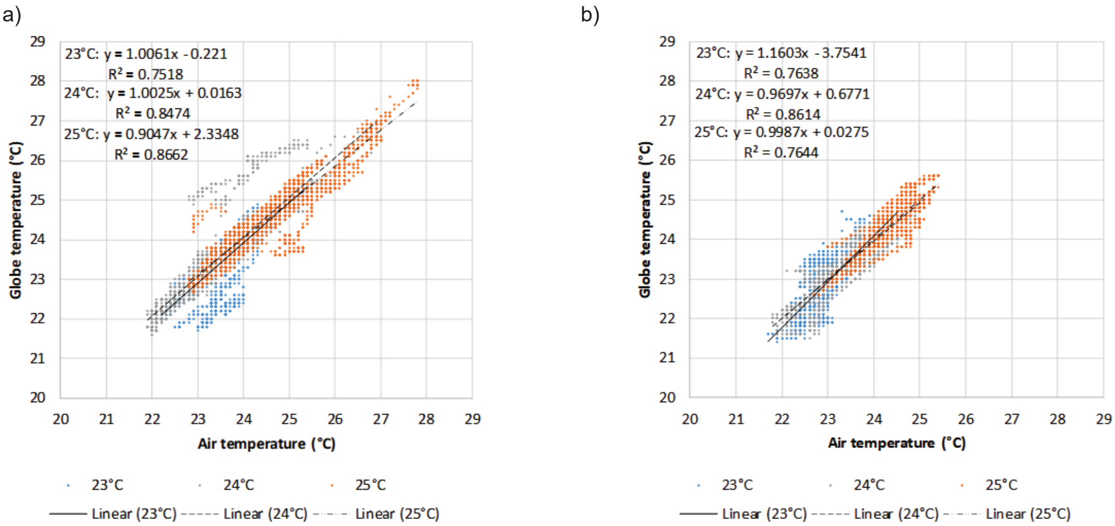


Figure 3:
Correlation between air temperature and globe temperature: a) Office A, b) Office B

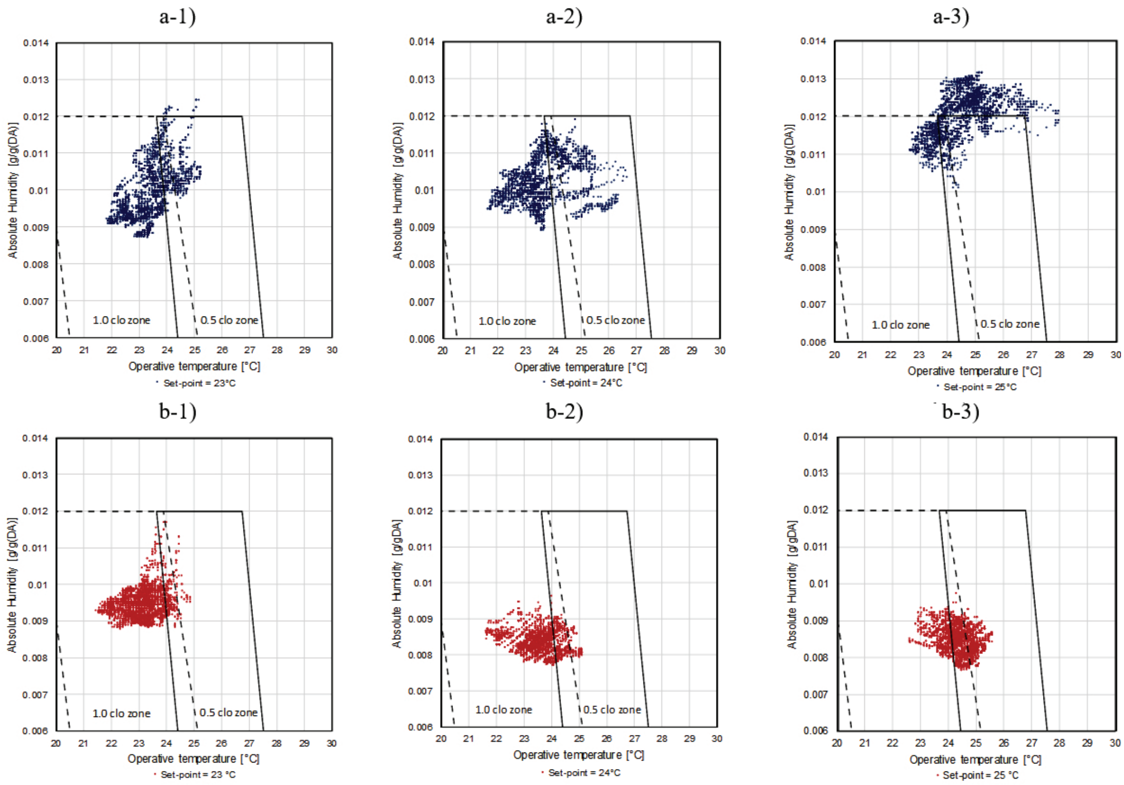


Figure 4:
Psychometric charts of ASHRAE55-2013 Standard: a-1) Office A at 23 °C, a-2) Office A at 24°C, a-3) Office A at 25 °C, b-1) Office B at 23 °C, b-2) Office B at 24 °C, b-3) Office A at 25 °C

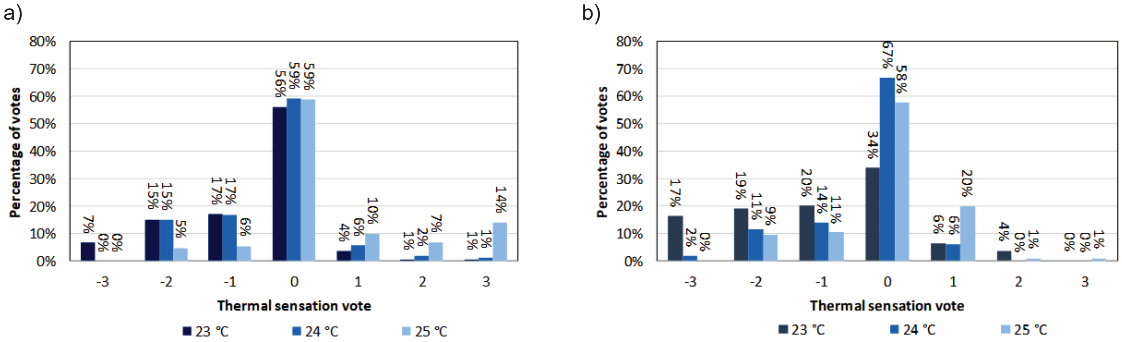


Figure 5:
Thermal sensation votes of case studies: a) Office A, b) Office B

counted as 56: 34: 10, 27: 64: 6, and 20: 58: 22. In Office B, the ratio was 39: 56: 5, 32: 59: 9, and 20: 58: 22. The percentage of neutral votes of Office B rapidly changed two times higher when we changed one higher set-point at 24 °C. Regardless of TSV = 0, the votes belonged to a colder-than-neutral side (-1 to -3) rather than a warmer-than-neutral side (1 to 3). When we set higher temperatures, more thermal environments changed to the recommended points between -1 and 1 that should be more than 80% of the total (ASHRAE, 2017). In Office A, the votes between -1 and 1 were increased from 77% to 82%, but it slightly decreased to 74% on the last day. In Office B, those votes increased from 61% to 87% and 88%, respectively. In terms of TSV, it was more suitable when changing higher temperatures to 24 °C or 25 °C. Especially, the rapid change happened in Office B which had more thermal environments in the 1.0 clo zone. The study was similar to a previous study in cellular rooms when the acceptable TSV at 24–25 °C was higher than that at 23 °C (Yamtraipat et al., 2006).

Thermal comfort votes (TCV) are shown in Figure 6. The percentage of comfortable votes (TCV = 1 and 2 or TCV+) was ranging from 29% to 35% (Office A) and from 30% to 35% (Office B). The rate of uncomfortable votes (TCV = -2 and -1 or TCV-) in Office A was 25%, 18%, and 26%, respectively, while that in Office B was 24%, 12%, and 20%, respectively. Regarding 20% of discomfort, thermal environments in Office A could meet up the requirement at 24 °C, while those of Office B was satisfied at 24–25 °C. The reason for high discomfort may cause by high relative humidity in a warmer environment which is sensitive to occupants who usually stay in a cold environment (Jing, Li, Tan, & Liu, 2013).

Figure 7 illustrates the relation between TSV and TCV by divided into 3 groups following the set-point. Both cases display a similar trend of sensation and comfort. People in a discomfort side (TCV-) gave the higher votes for feeling cold at 23–24 °C. In Office A, TSV- at 23 °C was the highest rate in the uncomfortable votes. TSV- of the slightly uncomfortable votes was reading

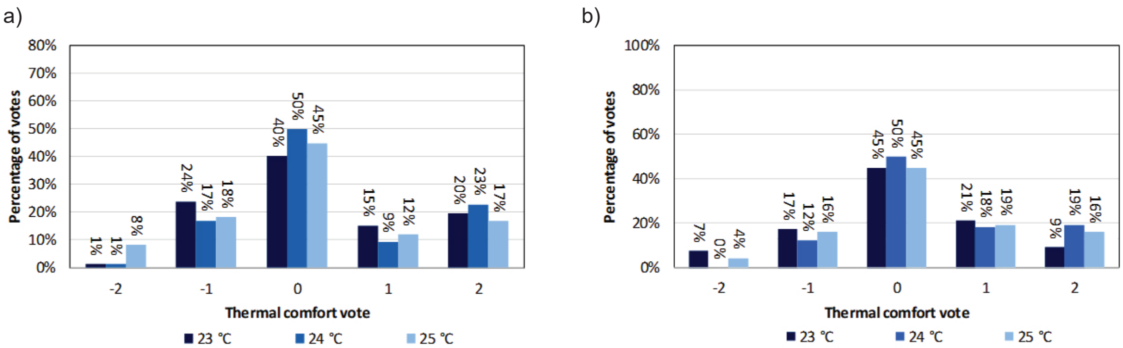
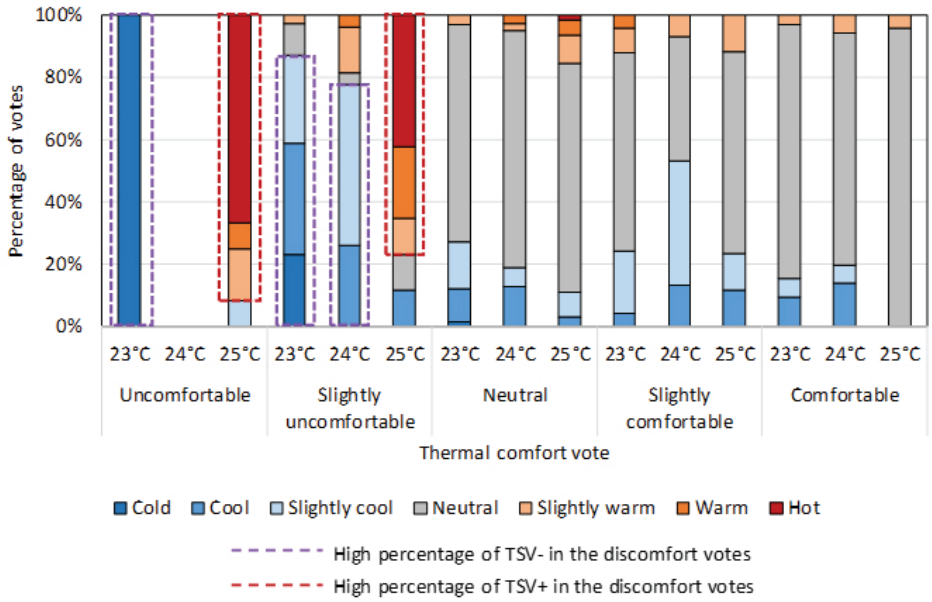


Figure 6:
Thermal comfort votes of case studies: a) Office A, b) Office B

as 87% at 23 °C and 78% at 24 °C, respectively (see the data in the purple dash line in Figure 7 (a)). In Office B, TSV- at 23 °C belonged to the uncomfortable votes by 88% and the slightly uncomfortable vote by 79% (see the data in the purple dash line in Figure 7 (b)). On the other hand, the discomfort votes highly changed to TSV+ when thermal environments were controlled at 25 °C. In Office A, TSV+ highly belonged to the uncomfortable votes (92%) and the slightly uncomfortable votes (77%) (see the data in the red dash line in Figure 7 (a)). Correspondingly, TSV+ of Office B matched with the uncomfortable votes (60%) and in the slightly uncomfortable votes (64%) (see the data in the red dash line in Figure 7

a)



b)

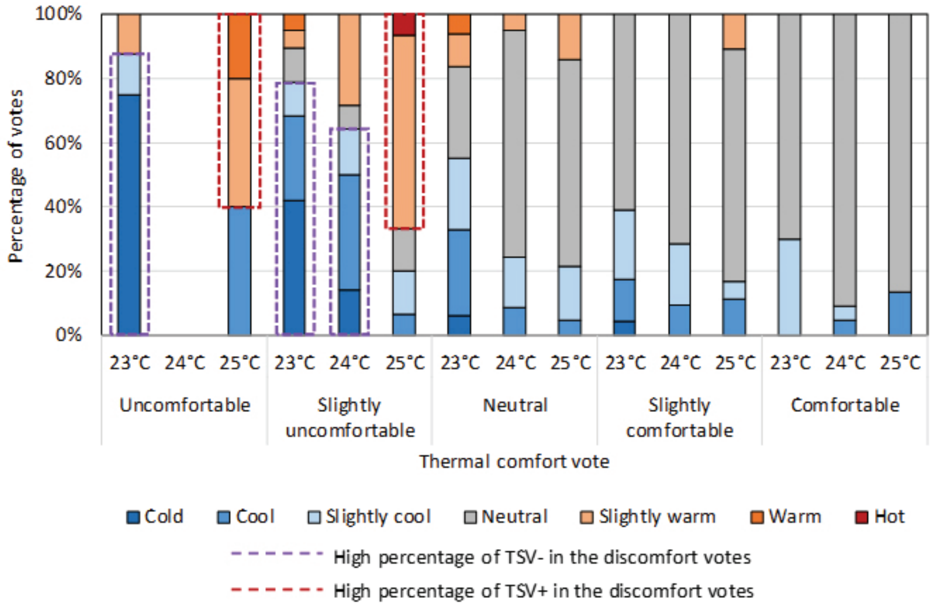


Figure 7:
Relation between TSV and TCV: a) Office A, b) Office B

(b)). The comfortable votes were mainly derived from people who voted for the neutral side and the cold side. TSV = 0 declared the comfort votes ranging from 40% to 96% (Office A) and from 61–91% (Office B). The comfortable votes of TSV- show the value from 15% to 23% (Office A) and from 10 to 39% (Office B). TCV on the second day (24°C) was the most effective when no one voted for feeling uncomfortable (TSV = -3 or +3).

The thermal acceptance votes (TAV) are shown in Figure 8. This kind of voting provided two choices to be chosen in order to confirm the decision of occupants whether thermal environments they exposed to was acceptable or not. We found that the unacceptable rate on the first day was lower than that on the second day. If we count 80% of acceptability, thermal environments in Office A were acceptable on the first day and the second day while those of Office B were acceptable for all three days. It is identified that increasing 1 degree Celsius higher (24 °C) was most acceptable, nevertheless, occupants in Office A accepted to stay at 23 °C more than at 25 °C.

The thermal preference votes in Figure 9 was determined by asking whether occupants preferred to change the temperature in the office or not. On a normal set-point day, although most of them in both offices answered that they did not want to change the temperature (64%, and 51%, respectively), there was 28% of them in Office A and 36% of them in Office B preferred warmer temperatures. The colder temperature preference was significantly lower than the warmer temperature preference. When we changed into a warmer temperature, the colder temperature preference reduced from 28% to 7% (Office A) and 36% to 10% (Office B). The ratio between the “prefer-colder” votes and the “prefer-warmer” votes of Office A was reading as 13:36, 8:18, and 21:10, respectively. It was similar trends with that of Office B which was 13:16, 8:19, and 21:10, respectively. Correlation between TSV and TPV was found to be a negative value (-0.59) at the 0.01 significant level (2-tailed). Occupants who felt cold preferred warmer temperatures and ones who felt warm preferred to change temperature into colder.

a) b)

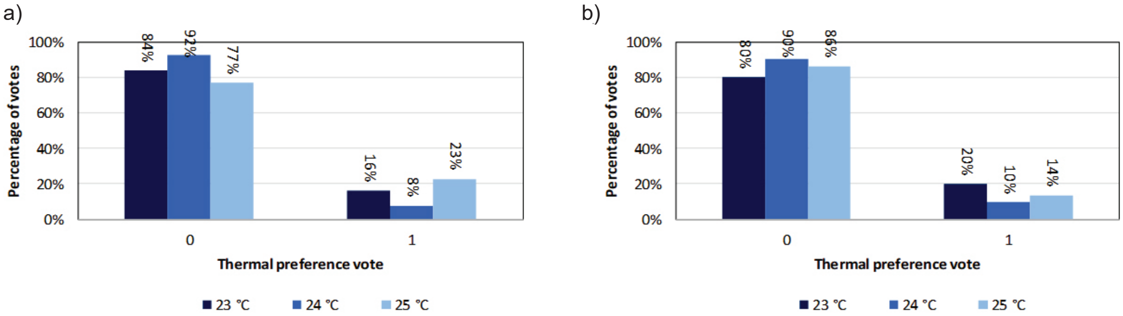


Figure 8:
Thermal acceptance votes of case studies: a) Office A, b) Office B

a) b)

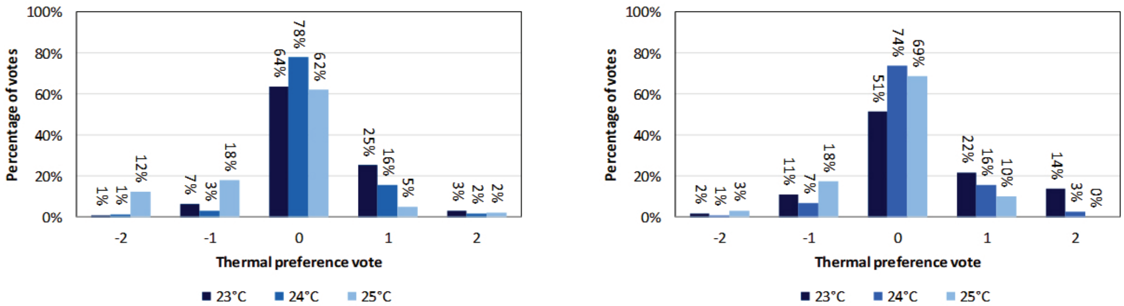


Figure 9:
Thermal preference vote of case studies: a) Office A, b) Office B

The PMV calculation was listed in Table 5. Data were derived from the questionnaire at 11:00 and 15:00 comparing with collected thermal variables. At the normal condition, most of the values were mainly below -0.5 in both cases which were 38% (Office A) and 75% (Office B). The estimation tended to be out of the recommendation zone (PMV= - 0.5 to 0.5) due to the low air temperature. The percentage of PMV fitted with the ASHRAE standard gradually increased (Office A = 57%, 62%, and 89%, respectively, Office B = 25%, 48%, and 71%, respectively). It could be concluded that in terms of PMV, the best values were in the warmest at 25°C. We also calculated a difference between PMV and TSV, it was found that PMV is different from TSV by 0.1 to 1 in Office A, and 0.1 to 0.3 in Office B. The average of the questionnaire was added into Table 6. The average PMV and TSV were quite similar on the first day, however, when changing higher temperatures, that of TSV deviated from the negative value to the positive value higher than that of PMV. TSV is more sensitive in a change in operative temperature rather than PMV.

The comfort operative temperature was derived from the Griffiths' method (Griffiths & Communities, 1991) which could be applied for several building types and climate zones including office buildings in the tropics (Humphreys, Rijal, & Nicol, 2013). The equation is $T_c = T_r\ (0 - C)/a$, where T_c means the comfort temperature (°C), based on T, which is temperature (°C); C is the thermal sensation vote on the scale, where 0 defines as a neutral condition; and a defines the constant rate of thermal sensation change with the room temperature. In this study, 0.5 was used as the constant value, as had been used with a seven-point thermal sensation scale by the study of Humphreys (Humphreys et al.) As the results, the average operative comfort temperature was found to be 23.6–24.8 °C in Office A, and 23.9–25.1 °C in Office B. It did not become a big gap when changing such rapid temperatures. Considering the estimation in Table 7, when we compare the measured operative temperature with the comfort temperature, it is applied that changing higher temperatures could be possibly adjusted by +2 °C. However, these cases must be carefully concerned about high relative humidity which directly affects human comfort, especially in Office B which the actual temperature was near to the comfort temperature, but people voted for discomfort up to 26%.

Table 5: The PMV Estimation

Set-point (°C)	Item	PMV < -0.5	-0.5 ≦ PMV ≦ 0	0 ≦ PMV ≦ 0.5	0.5 < PMV	Comply with ASHRAE standard 55-2017	Does not comply with ASHRAE standard 55-2017
Office A							
23	N	64	73	23	8	96	72
24		54	71	28	6	99	60
25		8	70	54	8	124	16
23	%	38	43	14	5	57	43
24		34	45	18	4	62	38
25		6	50	39	6	89	11
Office B							
23	N	82	22	5	0	27	82
24		44	32	23	16	55	60
25		1	59	9	27	68	28
23	%	75	20	5	0	25	75
24		38	28	20	14	48	52
25		1	61	9	28	71	29

Table 6: Average Values of PMV and the Subjective Votes

Set-point (°C)	Items	PMV	TSV	TCV	TAV	TPV
Office A						
23	Mean	-0.4	-0.6	0.3	0.2	0.3
	SD	0.5	1.1	1.1	0.4	0.6
24	Mean	-0.4	-0.3	0.4	0.1	0.1
	SD	0.5	1.0	1.1	0.3	0.5
25	Mean	-0.4	0.6	0.1	0.2	-0.3
	SD	0.4	1.4	1.2	0.4	0.8
Office B						
23	Mean	-0.7	-1.0	0.1	0.2	0.3
	SD	0.6	1.4	1.0	0.40	0.9
24	Mean	-0.3	-0.4	0.4	0.1	0.1
	SD	0.8	0.9	0.9	0.34	0.6
25	Mean	0.1	0.0	0.2	0.1	-0.1
	SD	0.4	0.9	1.1	0.34	0.6

Table 7: The Comfort Operative Temperature Estimation

Set-point (°C)	Number		Item	Comfort operative temperature (°C)	
	Office A	Office B		Office A	Office B
23	168	109	Min	17.6	19.0
			Max	29.6	30.0
			Mean	24.8	25.1
			SD	2.0	2.7
24	159	96	Min	17.7	17.3
			Max	28.0	28.5
			Mean	24.5	23.9
			SD	1.8	1.8
25	140	96	Min	18.1	18.7
			Max	29.3	29.4
			Mean	23.6	24.8
			SD	2.6	1.8
All	467	301	Mean	24.3	24.6
			SD	2.2	2.2

Thermal adaptive behavior

Thermal adaptive behavior is self-adaptation of people to be comfortable in thermal environment (Nicol, Humphreys, & Olesen, 2004). Initially, a study was conducted in free-running mode buildings and later extended to cooling-mode buildings (Rijal, Humphreys, & Nicol, 2017). Some adaptive behaviors, such as changing clothes and opening a portable fan were found to be a higher rate in Southeast Asian countries (Damiati et al., 2016). The results reveal that occupants in a tropical region tolerate cooling conditions more than those in Japanese offices with a high number of warmer-than-neutral votes. Also, the study in Singapore (Chen & Chang, 2012) found that the clothing insulation was added during the day which was that of males were 0.57 clo and that of females were 0.61 clo on average. To understand air-conditioning experience of occupants, we also asked occupants what the temperature set-point that they usually set at home. There were over 50% of them setting the thermostat at 25 °C while 19% of them set the point lower than 25 °C. It is implied that most people lived at warmer temperatures at home and experienced colder temperatures in the office. People were aware of the cool condition in the office so they had to prepare themselves to stay inside the office building. This issue led to the adaptive behavior in the office that the occupants prepared some belongings to adjust themselves in the office. In this single-blind study, we did not control clothing behavior because we aimed to observe automatic responses and the impact of sudden thermal environment changes. If we informed to control the clothing rate, people would notice the change and easily gave different feedbacks or tolerated such cool temperatures. The clothing insulation changing rate of case studies were added in Table 8. Clothing insulation of occupants was checked at 9:00, 11:00, and 15:00. We did not notice a difference in the clothing rate between males and females in these cases. The percentage of belongings mostly was found to be clothing of the upper part. In Office A, the rate of people wearing suits was high because of company uniforms. In addition, the mean clothing rate slightly increased from 0.61 clo to 0.65 clo. when some occupants worn additional cloths; light jackets, sweaters, cardigans, and scarves. The increase of average on the first day was slightly higher than that on the last two days. One the first day, the average clothing rate in Office A started at 0.61 clo and inclined to 0.65 clo in the afternoon because people felt cold. When the set-point was 25 °C, the average declined from 0.61 clo 0.56 clo, nearly the expected value (0.5 clo). These results point that warmer temperatures could reduce the adjustment of cloths. Additionally, a similar trend happened in Office B when an increase of clothing was the highest on the first day from 0.53 clo to 0.59 clo and then decreased in the last two days. Occupants who wore summer clothing and stayed in the cool environment easily felt cold and preferred warmer temperatures. A similar study of clothing adaptation is mentioned in other offices in Thailand when indoor temperature became lower than 23 °C (Sikram, Ichinose, & Sasaki, 2019). Therefore, clothing change at the temperature up to 25 °C remains acceptable.

Table 8: The Clothing Insulation Changing Rate

Set-point	N	Item	9:00	11:00	15:00
Office A					
23	91	Clo_{av}	0.61	0.65	0.65
		SD	0.17	0.22	0.22
24	85	Clo_{av}	0.58	0.62	0.60
		SD	0.17	0.21	0.16
25	77	Clo_{av}	0.61	0.60	0.56
		SD	0.19	0.17	0.15
Office B					
23	58	Clo_{av}	0.53	0.57	0.59
		SD	0.12	0.10	0.12
24	59	Clo_{av}	0.54	0.56	0.56
		SD	0.08	0.07	0.11
25	57	Clo_{av}	0.54	0.55	0.54
		SD	0.09	0.10	0.13

Note: Clo_{av}: average clothing value

CONCLUSIONS

In this study, a field investigation was conducted in two air-conditioned offices in Bangkok metropolitan, Thailand. In order to improve thermal comfort, the room temperature set-point was adjusted between 23–25 °C. Thermal performance of each day will be estimated together with the questionnaire survey. Thermal environments in office spaces of both cases were generally in the 1.0 clo comfort zone rather than 0.5 clo zone because the low-temperature point at 23 °C produced indoor thermal environment to be overcooled. When we change to higher temperatures, it was noticeable that the average temperature was changed close to the set-points. Thermal environments and occupants' characteristics in warmer temperatures were appropriated for PMV which most values shifted from a negative side to a positive side. According to TSV, at the set-point of 24 °C could enhance occupants as the highest acceptable votes of comfort, sensation, and preference, however, the votes from occupants in Office B at the set-point of 25 °C was still agreeable within 80% satisfaction. The clothing rate was found to be suitable to the 0.5 clo zone and adaptive clothing behavior reduced when changing to warmer temperatures. To apply to existing buildings, thermal environments should improve by following the estimated comfort temperature at 23.6–25.1 °C when people worn summer clothing between 0.5 clo to 0.6 clo. We notice that there were many people feeling discomfort when the operative temperature was higher than the comfort temperature. The main reason was relative humidity went higher than 60% when the temperature was set warmer. The humidification performance of this air-conditioning system must be carefully considered when temperature was increased. According to the previous study in Singapore (Chen & Chang, 2012), an effective air-conditioning performance to the new office is challenging to reduce humidity levels from outside. The development of separated dehumidification should be more concerned when designing AC so that temperature would not be too cold and humidity is well controlled at optimum values. Nonetheless, this study does not mention energy performance, it would be more beneficial to understand the importance of an increase of set-point from different perspectives. We encourage a future study to be related to this topic.

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