Accepted Manuscript

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PII: S0378-7788(18)33342-5
DOI: <https://doi.org/10.1016/j.enbuild.2019.05.030>
Reference: ENB 9191

To appear in: *Energy & Buildings*

Received date: 30 October 2018
Revised date: 8 May 2019
Accepted date: 13 May 2019

Please cite this article as: Maryam Khoshbakht , Zhonghua Gou , Fan Zhang , A pilot study of thermal comfort in subtropical mixed-mode higher education office buildings with different change-over control strategies., *Energy & Buildings* (2019), doi: <https://doi.org/10.1016/j.enbuild.2019.05.030>

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Highlights

- A pilot study in three mixed-mode change-over buildings in subtropical climate was performed.
- A new definition for mixed-mode classification was proposed particularly relevant to thermal comfort studies.
- Occupant thermal expectation and satisfactions was different across the three change-over mixed-mode buildings with different control strategies.
- Mixed-mode change-over control strategy seemed to be an important influencing factor in thermal comfort sensations.

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A pilot study of thermal comfort in subtropical mixed-mode higher education office buildings with different change-over control strategies.

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Abstract

Change-over mixed-mode buildings prevent the concurrent use of air-conditioners and operable windows, thus are energy-efficient. Based on automation levels for mixed-mode control, change-over mixed-mode buildings can be classified into three types: *automated*, *semi-manual*, and *manual*. The objective of this research was to conduct a pilot study on the effects of different change-over mixed-mode control strategies on building occupants' thermal perception and comfort, as well as develop adaptive comfort models for mixed-mode buildings with different change-over control strategies in subtropical climates. Occupants from three types of mixed-mode control buildings were surveyed about their real-time thermal perception, while indoor environmental conditions were recorded simultaneously for a period from summer to winter. Although an overlooked factor in previous studies, this pilot study suggests that change-over control strategy may significantly affect thermal perceptions in mixed-mode buildings. Occupants who had limited control over thermal environments showed less sensitivity to outdoor conditions regardless of operation modes. In buildings where, users had a full control, a clear distinction in thermal sensation was observed when the system switched between air conditioning and natural ventilation modes. The adaptive thermal comfort model seems to be more suitable and applicable for semi-manually and manually controlled mixed-mode buildings rather than for automatically controlled mixed-mode buildings.

Keywords: Mixed-mode ventilation; change-over control; thermal comfort; adaptive comfort model

Nomenclature:

TSV	Thermal sensation vote
AC	Air conditioning
NV	Natural ventilation
MM	Mixed-mode building
HVAC	Heating, ventilation, and air conditioning
IEQ	Indoor environmental quality
T_a	Air temperature
T_{op}	Operative temperature
MRT	Mean radiant temperature
T_g	Globe temperature
V_a	Air velocity
RH	Relative humidity

clo Clothing insulation

$T_{pma(out)}$ Prevailing Mean Outdoor Air Temperature

SD Standard deviation

G Griffiths' constant

1. Introduction

1.1 Mixed-mode (MM) buildings and different control strategies

Energy consumption in the building sector has drastically increased over the past few decades, exceeding other major sectors, including industry and transportation, due to factors such as global climate change, more time spent indoors, and increased demand for building services and comfort levels [1]. The upsurge in demand for HVAC (heating, ventilation and air conditioning) systems has been significant [2]. In particular, the growing use of air-conditioning (AC) is predicted to be one of the top drivers of global electricity demand over the next three decades [3]. Accordingly, there is an urgent need to reduce cooling energy demands by seeking alternative solutions to AC. Natural ventilation (NV) has been an increasingly attractive method, not only to reduce cooling energy demand, but also to provide a healthy, comfortable, and productive indoor environment for building occupants. However, NV may not be suitable for the whole year, particularly in subtropical climates with warm and humid summers. Therefore, mixed mode (MM) systems, a hybrid approach to space conditioning which utilises a combination of AC and NV, demonstrate valuable superiorities over the separate use of AC and NV systems, particularly in terms of energy saving potentials and providing thermal comfort for the whole year.

Based on the integration of NV and AC control strategies, especially whether they exist in the same spaces, or operate at the same time, MM buildings can be categorised into three types: *zoned*, *concurrent*, and *change-over* [4]. In *zoned* MM buildings, various spaces within the building have different conditioning strategies, that is, NV and AC operating in various spaces at the same time [5]. In *concurrent* MM buildings, NV and AC operate in the same space and at the same time [5]. In *change-over* types, MM buildings switch between NV and AC on a daily or seasonal basis. Although *concurrent* MM operation is the most prevalent strategy in the current practice [4], running NV and AC systems at the same time is not energy-efficient. The *change-over* system, on the contrary, has a control strategy to prevent concurrent operations of air-conditioning systems and operable windows. This paper only discusses *change-over* MM buildings and their capacities to provide thermal comfort for building occupants.

Based on the level of automation for MM control, change-over MM buildings can be classified into three types: *automated*, *semi-manual* and *manual*. In *automated* change-over MM buildings, the operation of the windows and AC system is controlled *entirely* by building automation systems (BAS), which switch between operation modes based on predefined algorithms, for example, indoor/outdoor temperatures, number of occupants, and outdoor wind speed. Change-over MM buildings with *semi-manual* control have the same BAS control over the operation of NV and AC systems, but occupants have the opportunity to manually override the BAS control by switching between operation modes on the control panel located in the occupied space. In *manual* MM buildings, occupants have full control of the window operation and AC systems. There can still be a BAS in these buildings; however, the use of BAS is limited only to shutting down AC systems when windows are being opened.

The three types of change-over control each have their advantages and disadvantages. Automated control utilizes smart sensors to monitor indoor and outdoor climate conditions and relies on computational intelligence to predict user preferences as the logic of control. Nevertheless, building occupants tend to lose the adaptive opportunities in these buildings; also, the initial and maintenance

costs of complex BAS are relatively high [5]. The manual change-over control allows for a higher degree of user control over the indoor environment. However, manual control may still result in a waste of energy due to overcooling/overheating of the spaces. Semi-manual control combines automated and manual control. While building automation and smart control are relatively new, there is a lack of post-occupancy studies in change-over MM buildings with different control strategies.

1.2 Thermal comfort under different control strategies in change-over MM buildings

However, the interest in the concept of MM buildings faces a variety of concerns and design challenges. One of the main concerns is the lack of predictability and thermal comfort models for MM buildings [5]. The steady-state model of thermal comfort, or PMV/PPD, was first introduced by Fanger in 1970 [6], when he studied thermal sensations in AC chambers and found steady correlations between building occupants and their immediate indoor thermal environments. The ASHRAE adaptive thermal comfort model was previously developed in NV buildings by de Dear and Brager [7], which suggests that occupants in NV buildings prefer a wider range of thermal conditions than in AC buildings. Another adaptive thermal comfort standard, EN15251, for free running modes was developed based on a one-year longitudinal survey in 26 offices in Europe [8]. Both standards, ASHRAE and EN15251, contain linear equations correlating acceptable indoor temperatures with prevailing outdoor temperature, and are very similar apart from a 1 K difference between the y-intercepts of the equations [9].

Due to the hybrid nature of space conditioning, there has been controversy over which thermal comfort model is applicable in MM buildings [5, 10]. Also, until now, thermal comfort standards for MM buildings have not been developed [6, 11, 12], nor are there frameworks about the optimum control strategies or the relative degree of automation that MM buildings should provide [4]. Table 1 provides an overview of previous studies that examined occupant comfort in MM buildings with different change-over control strategies.

Table 1. Summary of field studies regarding thermal comfort studies in change-over MM buildings.

Reference	Study year	Country/ Location	Climate	No of buildings	Building type	Suggested thermal comfort model	Separation of data based on operation mode	Change-over control
Drake et al. [13] Case study 2	2010	Australia	Subtropical	1	Higher education office	Adaptive thermal comfort	Yes	Automated
Deng et al. [14]	2017	Australia	Subtropical	1	Higher education office	Steady-state (winter) Adaptive thermal comfort (summer)	Not mentioned	Automated
Barbadilla-Martin et al. [15]	2017	Spain	Subtropical	3	Higher education office	Adaptive thermal comfort	No	Manual
Luo et al. [16]	2015	China/ Shenzhen	Subtropical	1	Office	Adaptive thermal comfort	Yes	Manual
Deuble and de Dear [10]	2012	Australia/ Sydney	Subtropical	1	Office	Adaptive model during NV mode; steady-state model during AC mode	Yes	Semi-manual
Manu et al. [17]	2016	India	Variable	13	Office	Adaptive thermal comfort	No	Manual
Rupp et al. [18]	2018	Brazil	Temperate and humid	3	Office	Adaptive thermal comfort	Yes	Manual
De Vecchi et al. [19]	2017	Brazil	Subtropical	3	Office	Not mentioned	Yes	Manual
Rijal et al. [20]	2017	Japan	Temperate	11	Office, Higher education office	Adaptive thermal comfort	Yes	Manual

ASHRAE 55 [21] recommends that MM buildings should be treated as AC buildings in terms of thermal comfort evaluation. However, as is shown in Table 1, only Deng et. al's study [11] partly supports this assertion. They examined a building with automated change-over MM control, and concluded that steady-state models are more applicable in winter in MM buildings, while adaptive thermal comfort models provide a better prediction of comfort in summer. Deuble and de Dear [10] suggested using different thermal comfort models during different modes of operation, due to a significant bifurcation in thermal perceptions when the MM building switches between AC and NV modes. All other reviewed studies except, De Vecchi et al. [19], supported the use of the adaptive comfort model for change-over MM buildings during both NV and AC modes [10, 13, 15-18, 20]. Rupp et al. [18] studied three office buildings in Brazil and found no evidence to support either a single thermal comfort model for the three MM buildings or the recommendation by ASHRAE 55 to evaluate MM buildings as AC buildings.

Previous research has not yielded consistent findings on the effect of operation modes on thermal perceptions. Barbadilla-Martin et al. [15] and Manu et al. [17] have proposed the use of a single adaptive thermal comfort model in MM buildings, for both AC and NV modes of operation. Other studies [10,13,14,16-18] assert that occupants' thermal perceptions differ from NV and AC modes; thus data should be separately analysed.

As mentioned above, previous literature failed to reach a consensus on what thermal comfort models should be adopted for MM buildings, or whether the mode of operation would have an impact on thermal perception. It was also evident that most previous studies were conducted in MM buildings with manual change-over controls, while MM buildings with automated and semi-manual controls were rarely studied. The objective of this research was to carry out a field study in occupants' thermal

comfort under different change-over control strategies in MM office buildings located in subtropical climates. Specifically, this study:

1. compares thermal perceptions in MM buildings with different change-over control strategies.
2. tests the effect of operation modes on occupants' thermal perception in different change-over MM buildings.
3. explores the applicability of adaptive thermal comfort models to MM buildings with different control strategies.

2. Methodology

Thermal comfort studies can be classified into two classes: laboratory studies and field studies [9]. This paper adopted a field study to develop thermal comfort models based on statistical techniques.

2.1 Surveyed buildings

Three MM buildings representing the three change-over control strategies were surveyed from February 2017 to July 2017. An overview of the building exterior and characteristics are shown in Figure 1 and Table 2. The three MM office buildings all belong to the higher education sector. Building A (automated change-over MM building) and Building B (semi-manual change-over MM building) are located in Brisbane, Building C (manual change-over MM building) is located on the Gold Coast. Both cities have a Mediterranean subtropical climate, characterized by a hot and humid summer, and a mild winter. In Brisbane, the average daily outdoor temperature ranges from 10.2 °C in July (winter) to 30.3 °C in January (summer) [22]. On the Gold Coast, the average daily outdoor temperature ranges from 12.0 °C in July (winter) to 28.7 °C in January (summer) [22]. Relative humidity ranges between 55% and 72% for the Gold Coast, and 44% and 70% for Brisbane [22] (see Figure 2).

Fig 1. Three MM buildings for field studies: (a) Building A, (b) Building B, (c) Building C.

Fig 2. Summary statistics of mean monthly temperature and relative humidity for a period from 2000 to 2017 for the Gold Coast (a); and Brisbane (b).

Table 2. The characteristics of the studied buildings.

ID	Change-over control strategy	Green building certificate	Location	Climate	Year	GFA (m2)	Interior layout	HVAC system	Air distribution	Orientation
A	Automated	5 Green Star	Brisbane	Mediterranean subtropical	2014	18,000	Mostly open plan	Zoned variable-air-volume	Displacement ventilation through desk vents	North South
B	Semi-manual	6 Green Star	Brisbane	Mediterranean subtropical	2013	3,865	Mostly open plan	Hydronic cooling	Displacement ventilation through desk vents	North-East South-West
C	Manual	6 Green Star	Gold Coast	Mediterranean subtropical	2007	1,400	Mostly private	Split units	Overhead air distribution	North-West South-East

All three buildings consist of offices, laboratories, conference and meeting rooms, and breakout spaces. Only office spaces were selected for the investigation of thermal comfort, including open-plan offices and cellular offices. In Building A, three open plan offices were selected, which accommodated spaces for higher degree research students and postdoctoral researchers. In the semi-manual building, two open plan offices accommodating research and academic staff were chosen for the study. Surveyed offices in the MM building with manual control included two open plan offices and 32 cellular offices located on two different floors. Surveyed offices were highlighted in red in a typical floor plan for all three buildings, as shown in Figure 3.

Fig 3. The location of surveyed offices: (a) Building A, (b) Building B, (c) Building C.

Building A has an atrium at its centre, allowing occupants to access all levels, while accommodating research laboratories on one side of the atrium and open plan offices on the opposite side. Control of the operation mode is automated by BAS, which automatically switches from AC to NV if the outdoor temperature falls within a temperature range between 22 °C and 26 °C. The cooling system of the building consists of water-cooled chillers which use tempered air by phase change materials embedded in a thermal labyrinth. Conditioned air is distributed at work stations through desk vents, where occupants can only adjust the direction of the incoming air.

Building B features a central atrium and a green wall. The ground floor is dedicated to visitors, while the two upper floors include meeting spaces, seminar rooms, and open plan offices for staff. The building is equipped with an evaporative cooling and dehumidification system, programmed to deliver 18 °C air at 55% relative humidity at work stations. In winter, the supplied air is heated by a hot water tank before being distributed through desk vents. The BAS activates the HVAC if outdoor temperatures rise above 28 °C. Dehumidification is carried out if needed by pumping air into a silica gel desiccant wheel to remove moisture. In contrast to Building A, occupants in Building B have the opportunity to manually override the automated control through the BAS interface in the open-plan office. Occupants can manage the operation of the building and switch between active and passive cooling. For example, users can switch off the active cooling and trigger the opening of the windows.

Building C accommodates studio spaces, workshops, and a seminar room on the ground floor, while the two upper floors provide offices and meeting rooms for academic staff and research students. This building offers individual AC control in each office, where occupants can choose between NV and AC. Occupants can open and close windows, but to facilitate efficient use of energy, the BAS in the building prevents the concurrent running of NV and AC, meaning the AC will be deactivated once windows or doors are open. In Building C, no blinds for occupant control of solar radiation is provided and only louvre awnings are utilised for solar protection.

2.2 Participants

In total, 1001 responses were collected from 208 volunteer participants in the survey. Participants were mainly students and staff members of the university where the surveyed building was located. In

this study, only volunteers who had worked in the building for more than one year were selected, to ensure that subjects were fully adapted to the local climate. The demographic features of the participants are shown in Table 3. Participant clothing insulation, metabolic rates and fitness levels were recorded during the survey.

Table 3. Summary of demographic features of the participants.

ID	No. of studied offices	No. of participants			Age		
		Male	Female	Total	Male	Female	Mean
A	3 open plan offices	463	195	668	33	31	33
B	2 open plan offices	19	58	120	52	44	46
C	1 open plan and 33 cellular offices	55	28	96	47	51	49

Participants' average clothing insulation value was 0.51 *clo*, with a maximum value of 1 *clo* for participants wearing jackets and trousers, and a minimum value of 0.36 *clo* for people wearing t-shirts and shorts. The average metabolic rate recorded during the survey was 1.1 *met* for participants in sedentary typing activities, and the minimum metabolic rate was 1.0 *met* for participants in sedentary reading positions.

2.3 Questionnaires

Paper-based questionnaires were allocated to participants in order to assess their *right-here-right-now* thermal comfort perceptions [23, 24]. Instantaneous thermal sensation, perceived air movement, perceived humidity, perceived air quality, and perceived overall thermal comfort and productivity were investigated using a seven-point Likert scale, with values ranging from -3 to 3 (see Table 4). The real time surveys were conducted once a week in all three buildings from February to July, 2017.

Table 4. Thermal comfort and air quality questionnaires adopted in the survey.

Scale	Thermal sensation	Perceived air movement	Perceived humidity	Perceived air quality	Perceived overall thermal comfort and productivity
3	Hot	Too draughty	Too humid	Very fresh	Highly productive and comfortable
2	Warm	Draughty	Humid	Fresh	Productive and comfortable
1	Slightly warm	Slightly draughty	Slightly humid	Slightly fresh	Slightly productive and comfortable
0	Neutral	Neutral	Neutral	Neutral	Neutral
-1	Slightly cool	Slightly still	Slightly dry	Slightly	Slightly unproductive and uncomfortable
-2	Cool	Still	Dry	Stuffy	Unproductive and uncomfortable
-3	Cold	Too still	Too dry	Too stuffy	Very unproductive and uncomfortable

In addition, participant were surveyed about their preferences regarding real-time air movement, humidity, and air quality during the questionnaire, using a 3-point Likert scale of -1, 0 and +1 (for example, want warmer, no change, and want cooler).

2.4 Measurements

The instrumental measurements of indoor environmental quality (IEQ) parameters were conducted concomitantly with the questionnaire survey. During the survey period, indoor air temperature (T_a), globe temperature (T_g), relative humidity (RH), and carbon dioxide levels (CO_2) were measured and recorded at 5-minute intervals using IEQ monitoring devices, *Hux Connect*. Air velocity (V_a) was measured at the time of the subjective evaluations using handheld anemometers. In each open plan

office, four locations were selected for IEQ measurement with horizontally uniform distribution at 0.75m above the floor. The location of devices in a surveyed office is illustrated in Figure 4.

Fig 4. Equipment setup for measurements of T_a , RH, T_g and V_a ; sensors were placed at the work stations.

The *Hux Connect* set-up for each room consisted of one gateway and four motes. The gateway measured CO_2 , while the motes measured T_a , T_g , and RH. The average value of T_a , T_g , and RH from the four motes in each office room was calculated to represent indoor climate conditions and increase the accuracy of the measurements. The AC/NV mode status for each building was collected from BAS after the survey data collection was completed. A summary of instrument details, including accuracy and resolution, is presented in Table 5.

Table 5. Accuracy and resolution of instruments used in field measurements.

Parameter	Instrument / sensor	Trade name	Time interval (frequency)	Accuracy calibration	Resolution range
Air temperature (T_a)	Air Thermometer	<i>Hux Connect</i>	Continuous (every 5 minutes)	± 0.5 °C	5 to 60 °C
Globe temperature (T_g)	Globe thermometer	<i>Hux Connect</i>	Continuous (every 5 minutes)	± 0.5 °C	-25 to 85 °C
Air velocity (V_a)	Handheld anemometer	<i>Digitech</i>	At the time of survey	± 0.05 m/s	0 to 30.0 m/s
Relative humidity (RH)	Hygrometer	<i>Hux Connect</i>	Continuous (every 5 minutes)	$\pm 2\%$	10 to 70% RH
Carbon dioxide (CO_2)	CO_2 meter	<i>Hux Connect</i>	Continuous (every 5 minutes)	± 30 ppm	0 to 5000 ppm

2.5 Data collection and Analysis

A total of 1001 responses were collected from questionnaire surveys. In order to avoid bias in the study, survey responses from unwell or sick participants were excluded. In total, 871 individual responses were analysed.

2.5.1 Statistical analysis

A one-way ANOVA test, or analysis of variance, was conducted to determine whether there were statistically significant differences between the variable means in the three change-over control MM buildings. Post hoc analysis was also used for multiple comparisons with a Sidak adjustment. A linear regression analysis was performed between indoor comfort temperatures and the prevailing mean outdoor air temperatures to establish adaptive thermal comfort models. Multiple linear regression analysis was also employed to test the effect of operation modes and indoor operative temperature on participants' thermal sensation. For all analyses, the significance level was set to be $p < 0.05$.

2.5.2 Calculation of operative temperature

Due to the complexity of using multiple parameters, previous studies have recommended using a single index to estimate thermal sensation, such as *predicted mean vote* and *operative temperature* [15, 24]. Operative temperature (T_{op}) is also known as dry resultant temperature, which combines the effects of the mean radiant temperature (MRT) and air temperature (T_a). Operative temperature is estimated by Equation (1) for occupants engaged in near-sedentary physical activity, not in direct sunlight, and not exposed to air velocities greater than 0.10 m/s [25]. This was the case for participants in the survey, and accordingly, operative temperatures can be calculated from the following equation:

$$T_{op} = (MRT + T_a) / 2 \quad (1)$$

where T_{op} is operative temperature, MRT is mean radiant temperature, and T_a is air temperature.

Mean radiant temperature (MRT) was calculated based on the Equation (2), which was adapted from previous research [26] as the following:

$$MRT = \left[(T_g + 273)^4 + \frac{1.1 \times 10^8 \times V a^{0.6}}{\epsilon D^{0.4}} (T_g - T_a) \right]^{1/4} - 273 \quad (2)$$

where T_g , T_a , V_a , ϵ , D represent the globe temperature ($^{\circ}\text{C}$), air temperature ($^{\circ}\text{C}$), air velocity at the level of the globe (m/s), emissivity (0.95), and diameter of the black globe thermometer (0.035m), respectively.

2.5.3 Calculation of prevailing mean outdoor air temperature

Adaptive thermal comfort models correlate thermal sensations with outdoor temperatures. The adaptive thermal comfort hypothesis predicts that contextual factors and past thermal history modify user thermal expectations and preferences [27]. In the early studies the index of outdoor temperature was calculated based on the monthly running mean of the outdoor temperature [28, 29]. However, the latest research in adaptive thermal comfort studies has proved that an exponentially weighted running mean of the daily mean air temperature is a more accurate predictor as a responsive index for outdoor climate [30-33]. The input variable in the adaptive model is *prevailing mean outdoor air temperature* ($T_{pma(out)}$). This temperature is based on the arithmetic average of the mean daily outdoor temperatures over a period of days. It represents the broader external climatic environment which building occupants have physiologically, behaviourally, and psychologically adapted to [21]. $T_{pma(out)}$ can be calculated from the following equation based on ASHRAE-55 recommendations [34]:

$$T_{pma(out)} = (1 - \alpha) [t_{e(d-1)} + \alpha t_{e(d-2)} + \alpha^2 t_{e(d-3)} + \alpha^3 t_{e(d-4)} + \dots] \quad (3)$$

where α is a constant. ASHRAE 55 recommended α values from 0.9 to 0.6; a value of 0.9 could be more appropriate for humid tropics, and lower values more appropriate for mid-latitude climates. In this study, α value of 0.6 was adopted for the subtropical climate [18]. The $t_{e(d-1)}$, $t_{e(d-2)}$, $t_{e(d-3)}$, and further, are the 24 hour daily mean temperatures for yesterday, the day before and so on.

2.5.4 Calculation of comfort temperature

There are two methods of calculating comfort temperature: the linear regression method [7] and Griffiths' method [18]. The former utilises a linear regression between TSV (as a dependent variable) and indoor operative temperature (as an independent variable) and solves the equation by setting the dependent variable to the value of zero. This method has been widely used in previous thermal comfort studies [27]. However, as Nicol et al. [12] have pointed out, this method leads to bias in the estimation of comfort temperature if the mean thermal sensation deviates from neutrality. In this paper, Griffiths' method was adopted to calculate comfort temperature. Griffiths' method uses an

assumed value for the regression coefficient. Comfort temperature is calculated by the following equation:

$$T_{\text{comf}} = T_{\text{op}} - \text{TSV} / G \quad (4)$$

where T_{comf} is the comfort temperature ($^{\circ}\text{C}$), T_{op} is the indoor operative temperature ($^{\circ}\text{C}$), TSV is the thermal sensation vote, and G is Griffiths' constant ($^{\circ}\text{C}^{-1}$). Griffiths' constant of 0.5 has been observed as the most appropriate constant in previous studies [15, 17, 35].

3. Results and analysis

3.1 Thermal perceptions in different change-over MM buildings

Table 6 reports the measured indoor air temperature (T_a), globe temperature (T_g), air speed (V_a), relative humidity (%), CO_2 level (ppm), occupants' thermal sensation vote, and the calculated comfort temperature ($^{\circ}\text{C}$). The one-way ANOVA test was performed to identify the significance of differences in these mean values across the three buildings. Post hoc analysis was conducted to identify significant pairwise comparisons. The omnibus ANOVA tests detected significant differences in variable means in air temperature, globe temperature, relative humidity, CO_2 level and subjects' TSV. Post hoc analyses revealed that the mean T_a in Building B (27.0°C) was significantly higher than Building A (25.1°C , $p < 0.01$) and Building C (24.7°C , $p < 0.01$), but not significantly different between Building A and Building C. Similarly, the mean T_g value was significantly higher in Building B (27.9°C) than in Building A (26.0°C , $p < 0.01$) and Building C (26.1°C , $p < 0.01$). The T_g values were not significantly different between Building A and Building C. The mean RH level was 60%, 63%, and 61%, in Building A, Building B and Building C, respectively. Post hoc tests showed that only Building A had significantly lower RH values than Building B ($p < 0.01$). The mean CO_2 level in Building C (542 ppm) was significantly higher than in Building A (504 ppm, $p < 0.01$) and in Building B (444 ppm, $p < 0.01$). The mean TSV values were significantly higher in Building B (+0.48 TSV) building compared to both Building A (-0.48 TSV, $p < 0.01$) and Building C (-0.50 TSV, $p < 0.01$). The mean TSV values were not significantly different between Building A and Building C. The mean T_{comf} values in Building A, Building B, and Building C were 26.0°C , 26.3°C , and 25.7°C , respectively. ANOVA test showed no significant difference between these means ($p=0.197$).

Table 6. Summary of recorded IEQ parameters in three MM change-over control buildings.

ID	Variables	T_a ($^{\circ}\text{C}$)	T_g ($^{\circ}\text{C}$)	V_a (m/s)	RH (%)	CO_2 (ppm)	TSV	T_{comf}^a ($^{\circ}\text{C}$)
A	Mean	25.1	26.0	0.06	60	504	-0.48	26.0
	SD	0.8	1.0	0.11	9	44	0.90	2.0
	Min	23.4	24.2	0.00	42	433	-3.00	19.5
	Max	26.9	35.5	0.50	81	585	+3.00	31.9
B	Mean	27.0	27.9	0.06	63	444	0.48	26.3
	SD	4.5	4.5	0.15	9	47	1.43	3.0
	Min	14.0	13.9	0.00	8	25	-3.00	16.5
	Max	33.2	34.0	0.50	78	545	+3.00	32.1
C	Mean	24.7	26.1	0.06	61	542	-0.50	25.7
	SD	1.1	2.5	0.11	11	51	1.06	2.2
	Min	23.3	24.2	0.00	83	627	-3.00	21.5
	Max	27.6	40.1	0.40	44	446	2.00	31.1
Total	Mean	25.3	26.3	0.06	61	500	-0.35	26.0
	SD	1.8	2.0	0.11	9	48	1.05	2.2
	Min	19.8	20.7	0.00	42	411	-3.00	16.5
	Max	33.2	40.1	0.50	83	627	+3.00	32.1
ANOVA of mean value		$p < 0.01$	$p < 0.01$	NS	$p < 0.01$	$p < 0.01$	$p < 0.01$	NS

^a T_{comf} was calculated with Griffiths' method ($G=0.5$); NS: Not statistically significant.

3.2 Effects of operation modes on thermal sensation in different change-over MM buildings

In order to analyse whether thermal sensation differed from modes of operation, linear regression models were developed correlating TSV first with only indoor operative temperature T_{op} and then with both T_{op} and operation modes. Linear models considering raw data of indoor operative temperature and thermal sensation vote in three buildings were developed. As shown in Table 7, the R^2 values of the buildings A and C were very low. The regression models were not statistically significant either. This may be due to the relatively small sample size and the existence of outliers. As recommended by previous studies, correlating TSV with binned T_{op} decreases the negative effect of outliers and increases the significance of equations [10, 36]. Therefore, thermal sensation votes have been binned at 0.5 °C intervals of indoor operative temperature, and the regression model was weighted according to the number of votes falling in each of the bins. Table 8 shows the linear models obtained from correlating TSV with binned T_{op} data for the three buildings. The separation of data based on operation modes has been used by researchers in the past in buildings with manual MM systems [15, 17, 37].

Table 7. Linear regression models using raw data of indoor operative temperature and thermal sensation vote in different change-over control buildings.

ID	Linear models		N	S.E	Sig. F-change
	Model 1	Model 2			
A	TSV = 0.02 T_{op} - 1.03 $R^2=0.01$, $p=0.583$ S.E.(T_{op})=0.04	TSV = 0.02 T_{op} - 0.03 MO - 0.96 $R^2=0.01$, $p=0.767$ S.E.(T_{op}) = 0.04, S.E.(MO) = 0.07	668	0.90	0.632
B	TSV = 0.24 T_{op} - 6.24 $R^2=0.44$, $p<0.001$ S.E.(T_{op})=0.03	TSV = 0.24 T_{op} - 0.04 MO - 6.12 $R^2=0.44$, $p<0.001$ S.E.(T_{op})=0.05, S.E.(MO) = 0.38	120	1.07	0.928
C	TSV = 0.03 T_{op} - 1.15 $R^2=0.01$, $p=0.746$ S.E.(T_{op})=0.08	TSV = 0.06 T_{op} - 0.35 MO - 1.78 $R^2=0.03$, $p=0.366$ S.E.(T_{op}) = 0.08, S.E.(MO) = 0.25	83	1.06	0.169
All data	TSV = 0.22 T_{op} - 6.09 $R^2=0.15$, $p<0.001$ S.E.(T_{op})=0.02	TSV = 0.22 T_{op} - 0.03 MO - 6.04 $R^2=0.16$, $p<0.001$ S.E.(T_{op}) = 0.02, S.E.(MO) = 0.07	871	0.97	0.684

S.E. — coefficient standard error; Sig. F-change — significance of F-change.

Table 8. Linear regression models using binned indoor operative temperature and thermal sensation vote in different change-over control buildings.

ID	Linear model		N	S.E.	Sig. F-change
	Model 1	Model 2			
A	TSV = 0.16 T _{op} - 4.64 R ² =0.24, $p = 0.001$ S.E.(T _{op})=0.04	TSV = 0.15 T _{op} - 0.11 MO - 4.29 R ² =0.26, $p < 0.01$ S.E.(T _{op})=0.05, S.E.(MO) =0.11	46	0.36	0.354
B	TSV = 0.27 T _{op} - 6.86 R ² =0.64, $p < 0.01$ S.E.(T _{op})=0.03	TSV = 0.26 T _{op} - 0.24 MO - 6.59 R ² =0.65, $p < 0.01$ S.E.(T _{op}) =0.03, S.E.(MO) =0.23	55	0.84	0.295
C	TSV = 0.18 T _{op} - 5.17 R ² =0.10, $p=0.129$ S.E.(T _{op})=0.12	TSV = 0.20 T _{op} - 0.71 MO - 5.25 R ² =0.33, $p=0.013$ S.E.(T _{op}) =0.10, S.E.(MO) =0.26	25	0.62	0.013*
All data	TSV = 0.28 T _{op} - 7.56 R ² =0.63, $p<0.001$ S.E.(T _{op})=0.02	TSV = 0.28 T _{op} - 0.15 MO - 7.47 R ² =0.64, $p<0.001$ S.E.(T _{op}) =0.02, S.E.(MO) =0.12	126	0.68	$p<0.001$ ***

MO or operation mode is assumed 1 for NV and 0 for AC mode; S.E. — coefficient standard error; Sig. F-change — significance of F-change; * $p < 0.05$; *** $p < 0.001$.

Two models were developed for each building, one correlating TSV with T_{op} (model 1), and the other one correlating TSV with T_{op} and building operation mode (model 2). Comparison between two models represented by the R² change was tested with an F-test, referred to as the F-change. A significant F-change means that the variable (building operation mode) added in that step significantly improved the prediction. Table 8 demonstrates that the fitness of the linear model significantly improved when operation mode was added as an independent variable in regression model for Building C and all three buildings combined, meaning that building occupants' thermal sensation was significantly different between AC and NV modes in Building C and all three buildings combined. Figure 5 graphically represents regression lines correlating TSV and binned indoor operative temperature developed for AC and NV modes respectively in three MM buildings. The two trend lines are close to each other in Building A and Building B (Figure 5a, 5b), but are clearly detached in Building C (Figure 5c), which corroborates results in Table 8.

Fig 5. Thermal sensation correlating with indoor operative temperature during different ventilation modes (AC and NV) for: (a) Building A, (b) Building B, (c) Building C.

Comfort temperatures were calculated based on the regression equations in Table 8 and were compared the ones with previously calculated by Griffiths' method. As presented in Table 9, Building C observed the largest differences (3.5 °C) in comfort temperatures had the

significant difference between the two modes. Comfort temperatures calculated by linear regression models were generally higher than those determined by Griffiths' method.

Table 9. Comparison of Griffiths' comfort temperatures with comfort temperatures calculated with linear regression models of the studied buildings.

ID	Griffiths' T_{comf}^a (°C)	Comfort Temperature (°C) Under AC	Under NV
A	26.0	28.6	29.3
B	26.3	25.4	26.3
C	25.7	26.3	29.8
Total	26.0	26.7	27.2

3.3 Developing adaptive thermal comfort models for different change-over MM buildings

Table 10 presents the developed adaptive comfort models for the three change-over MM buildings. All four models have reached a high statistical significance level. However, looking at the coefficient of determination (R^2) for Building A, the prevailing outdoor temperature explains just 8% of the variance of the comfort temperature, compared to 48% in Building B, and 14% in Building C. Nonetheless, low R^2 values in the adaptive thermal comfort models are common in mixed-mode buildings as seen in previous studies (for example [18]).

Table 10. Adaptive thermal comfort models for different change-over MM buildings.

ID	N	Linear regression equation	R^2	S.E.	p
A	668	$T_{\text{comf}} = 0.16 T_{pma(out)} + 22.58$	0.08	0.02	$p < 0.001$
B	120	$T_{\text{comf}} = 0.48 T_{pma(out)} + 15.86$	0.48	0.05	$p < 0.001$
C	83	$T_{\text{comf}} = 0.23 T_{pma(out)} + 20.75$	0.14	0.07	0.001
All data	871	$T_{\text{comf}} = 0.24 T_{pma(out)} + 20.92$	0.17	0.02	$p < 0.001$

S.E. — coefficient standard error.

3.4 Comparison with previous studies

We categorized previous studies based on the mixed mode control systems to see how models fits with previous studies. Table 11 provides a summary of the comparison study. The model for building B shows the highest sensitivity of TSV to $T_{pma(out)}$ with the highest slope. In comparison with previous studies, The model developed for Building B was the most similar to the model developed by Rijal et al. based on a study in Pakistani buildings [37] and the model developed by Rupp, de Dear [18] based on Brazilian database. As illustrated in Figure 6, the slope of the equation developed for Building A and C was close to what Barbadilla-Martín, Lissén [15], Manu, Shukla [17] and Rupp, de Dear [18] found with Equation coefficient of 0.24 and 0.28, respectively. The R^2 values of our equations particularly for Building A and C were much lower than those obtained by previous studies. Nonetheless, this could be explained due to the total number of survey responses and the number of buildings in our study.

Table 11. The developed adaptive thermal comfort models in previous studies.

Ref	Adaptive thermal comfort Model	R ²
Barbadilla-Martín, Lissén [15]	$T_{\text{comf}} = 0.24 T_{\text{rm}} + 19.3$	0.41
Manu, Shukla [17]	$T_{\text{comf}} = 0.28 T_{\text{rm}} + 17.87$	0.72
Rupp, de Dear [18]	$T_{\text{comf}} = 0.56 T_{\text{pma(out)}} + 12.74$	0.89
Rijal, Humphreys [37]	$T_{\text{comf}} = 0.52 T_{\text{rm}} + 15.4$	0.79
Building A for current study	$T_{\text{comf}} = 0.16 T_{\text{pma(out)}} + 22.58$	0.08
Building B for current study	$T_{\text{comf}} = 0.48 T_{\text{pma(out)}} + 15.86$	0.48
Building C for current study	$T_{\text{comf}} = 0.23 T_{\text{pma(out)}} + 20.75$	0.14
All data for current study	$T_{\text{comf}} = 0.24 T_{\text{pma(out)}} + 20.92$	0.17

Fig 6. Comparison of adaptive thermal comfort model with previous studies.

4. Discussion

Currently, there is no standard protocol for the operation and control strategies for change-over MM buildings [11]. Based on this pilot study, MM control strategies may affect occupant thermal perceptions. Modes of operation in MM buildings significantly affected occupants' thermal sensation in Building C, but not in Building A and Building B.

Occupants in Building A were not consciously aware under which mode the building was running and their T_{comf} was less correlated with outdoor temperature conditions (the prevailing mean outdoor air temperature only explained 8% of the variance in TSV). In Building A, occupants' thermal perception seemed to resemble that in fully air-conditioned buildings. However, the calculated mean comfort temperature in Building A - 26.0 °C from Table 6 was much higher than the current common practice in Australia — the "22 °C setpoint" [38].

Although Table 8 suggests that modes of operation did not significantly affect TSV in Building B, they could also result from the inefficient control algorithm in this building. Building B was under AC mode only when the outdoor temperature rises above 28 °C. The control algorithm failed to provide a comfortable indoor environment, particularly in hot summer days, thus occupants overrode the BAS very often for natural ventilation, which further reduced the efficiency of the cooling system. This may be one of the reasons why thermal sensation votes were not significantly different between NV and AC operations.

In the building where users have a full control of the windows and AC systems, i.e., Building C, a clear distinction between TSV during AC and NV modes was observed, confirming the findings from previous studies in manual MM buildings that suggested the separation of data based on operation modes [16, 18-20]. There were also some studies that recommended the use of single thermal comfort models in manual MM buildings (for example, [15] and [17]). However, in Building C, users seem to be aware of the operation modes and actively adapt accordingly. As a result, the development of separate thermal comfort models for each operation mode seems more appropriate in manual MM buildings.

Some other factors may also contribute to the differences in thermal perception apart from MM control strategies. Participant age was much higher in Building B than those in Building A and Building C. Gender distribution in three buildings was slightly different. The average age in Building B and Building C was higher than those in Building A. In Building A and Building B, the surveyed offices had open-plan layouts, whereas in Building C most surveyed offices were cellular. These three factors—gender, age and office layouts—might have influenced thermal comfort perceptions in our study, yet it is impossible to control all variables in field tests and have the exact same number of participants from both genders, age groups and office layouts in different building types, particularly in surveys with big sample sizes. Although mixed-mode buildings have a great potential for subtropical climates, but unfortunately due to cultural and technical matters, case studies are scarce, that explains why no thermal comfort models are yet developed.

The lack of thermal comfort models further impacts the design and use of MM buildings. This study is a pilot study in MM buildings and has been purposed to progress in the development of thermal comfort models for MM buildings and promote the use of MM systems in suitable climates such as subtropical.

This pilot study offers an insight into the importance of change-over control types and their influence in occupants' thermal perception in MM buildings. As the literature review suggested, contradictory results were reported regarding the most appropriate thermal comfort models for MM buildings. This research suggests that change-over control strategies may explain some of the discrepancies in previous studies. In the study, only one building from each MM control type was studied and the developed thermal comfort models may have been affected by singularities of specific buildings. Apparently, more thermal comfort studies conducted in different types of change-over MM buildings are required in order to obtain more meaningful and consistent results.

Due to ethical limitations and the nature of the data collection in working and studying environments of higher education buildings, participant body mass index (BMI) values were not collected during the survey. The bias caused by differences in body fat was reduced by relying on surveyor judgment to exclude the involvement of occupants with significantly high body fat and very low fitness levels. Also, apart from gender, age and office layouts, there might be other variables that have contributed to the significant differences in occupants' thermal perceptions; however, these confounding variables were not identified in this study.

5. Conclusions

This paper reports a pilot study on thermal environments and building occupants' thermal perceptions in three types of mixed-mode higher education office buildings in subtropical climates with different change-over control strategies, namely, automated control, semi-manual control and manual control. The following findings are noteworthy:

1. Different change-over control strategies have an impact on the thermal environments and building occupants' thermal perceptions, and thus need to be considered in thermal comfort studies in mixed-mode buildings.
2. The TSV values were significantly higher in Building B (semi-manual) than those in Building A (automated) and Building C (manual).
3. There is no significant difference between comfort temperatures calculated by Griffiths' method for three types of MM buildings; however, comfort temperatures calculated by linear regression models observe clear differences.
4. When the operation mode switched between AC and NV, a clear distinction in thermal sensation was observed in Building C, where users had a full control of their thermal environments. However, TSV differences between modes of operation were not significant in automated or semi-manual MM buildings.
5. The adaptive thermal comfort model seems to be more suitable and applicable for Building B (semi-manual) and Building C (manual) rather than Building A (automated).

Acknowledgements

The authors would also like to thank all the survey participants and Hux Connect team involved in this project. Their time and input were invaluable and greatly appreciated. All funding for this project was provided by Griffith University as part of a PhD study. The authors would like to acknowledge the research team at Griffith University, particularly A/Prof Karine Dupre for her contribution to this project.

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