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Thermal comfort in a mixed-mode building: Are occupants more adaptive?

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Abstract: Mixed-mode (MM) ventilation approaches are becoming increasingly popular as a more energy efficient alternative to conventional HVAC solutions. By integrating both natural ventilation and mechanical cooling strategies, mixed-mode (or hybrid) building operation is able to achieve comfortable indoor environments whilst minimising reliance on energy intensive HVAC systems. This study investigated how different modes of operation in a mixed-mode building - air-conditioning (AC) and natural ventilation (NV) - affect indoor thermal environmental conditions and occupant perceptions of thermal comfort. Longitudinal field observations were made in a mixed-mode building located in subtropical climate area of Australia. Continuous indoor environmental quality (IEQ) data and building operational data such as HVAC system and windows states were collected, alongside right-here-right-now occupant comfort surveys. Time-and-place matching of these objective and subjective data streams enabled analysis of the relationships between building operational modes, indoor thermal environments, and occupant perception of comfort. The results indicate that the mode of ventilation influenced comfort responses of occupants beyond the direct effects of different thermal conditions. Occupants of the mixed mode building were more tolerant of, or adaptive to, the indoor thermal conditions when the building was in the NV mode of operation compared to the AC operational mode. Participants more actively thermoregulated their clothing insulation (*clo*) than what was predicted by the ASHRAE Standard 55's dynamic clothing model. These findings support the call for extending the scope of applicability of adaptive comfort standards to include mixed-mode buildings.

Keywords: Thermal comfort; mixed-mode; hybrid ventilation; clothing; adaptive behaviour

1. Introduction

The building sector consumes over 30% of global final energy consumption, and the provision of 'comfort' indoors (i.e. ventilation, space heating and cooling) typically accounts for the largest energy

end use [1]. Technological advances in Heating, Ventilation and Air-Conditioning (HVAC) have made it possible to tightly regulate indoor environments with minimal fluctuations over diurnal and seasonal timescales. However, this has come with significant energy costs from antagonistic operation of heating and cooling systems. In effect, the greatest proportion of building energy use is attributed to building services during the operational phase of a building's life. The International Energy Agency (IEA) estimates that space heating and cooling accounts for approximately 50% of final building energy consumption in OECD countries, and space cooling is reported to be the fastest-growing global energy end use [1]. HVAC is the largest end-use of energy in the Australian commercial property sector, responsible for typically more than half of commercial building energy use [2].

Contemporary HVAC temperature control deadbands are usually narrower than the comfort zones prescribed by comfort standards. For example, Mendell and Mier [3] reported that indoor temperatures in US office buildings in summer were cooler than the comfort thresholds prescribed in the relevant international standards [4,5] and, paradoxically, were even cooler than they were in winter. Likewise in Australia, a very narrow range of indoor air temperature ($22.5 \pm 1.5^\circ\text{C}$ in summer) is typically written into commercial office building boilerplate leases [6] despite ample empirical evidence from around the world indicating that tight and energy-intensive control of indoor temperatures does not translate into high occupant satisfaction [7].

While building services engineers and facility managers have focused on maintaining a steady and tight indoor temperature all year round, the research literature on adaptive thermal comfort suggests that an acceptable range of indoor temperatures in naturally ventilated (NV) spaces drifts in sync with the outdoor seasonal cycle (e.g.[8,9]). According to the adaptive comfort theory, the indoor comfort zone tracks prevailing outdoor weather – shifting up in warm weather and down in cool weather. As long as indoor temperature is maintained within the acceptable range appropriate to the season, it is possible for most building occupants to achieve thermal comfort. Accommodating this natural adaptability of occupants within the building's operation strategy has very positive implications for energy efficiency. Compelling empirical evidence indicates up to 30% HVAC energy saving can be achieved by relaxing the set-point temperature without sacrificing occupant comfort or satisfaction [10].

The mixed-mode (MM) building operation, which integrates both natural ventilation and air conditioning strategies, is deemed a viable alternative to the fully sealed-facade HVAC approach for both comfort [11,12] and energy efficiency [13]. Mixed-mode buildings allow internal spaces to be naturally ventilated through vents or operable windows whenever external conditions are favourable, but utilise mechanical systems if natural ventilation is unable to deliver comfort for the occupants. A classification scheme for MM buildings was proposed by Brager [12], including *a) concurrent*, in which mechanical cooling and natural ventilation operate simultaneously within the same part of the building, *b) changeover*, in which the operational mode switches between mechanical cooling and natural ventilation on the basis of externally and internally measured environmental data, and *c) zoned*, in which mechanical cooling and natural ventilation operate simultaneously in different parts of the building.

The shift between the two modes can be determined either manually by occupants or automatically by a building management system (BMS) supplied with real-time internal and outdoor environmental data. The main aim of MM is to maintain comfort by relying on natural ventilation as much as possible,

thereby minimising the energy penalty associated with operation of HVAC system. By employing appropriate design and operation strategies, MM buildings can simultaneously improve comfort and energy performance, especially in mild climates like Sydney Australia which are characterised by subtropical summers and mild winters with no extreme seasonal differences.

Despite the obvious benefits of MM strategies, there is ambiguity regarding which thermal comfort targets to use under the two different modes of operation in such buildings. For example, the relevant European standard, EN15251 [14], prescribes an adaptive comfort model for MM buildings operating under NV (or free-running) mode. In contrast, the current version of ASHRAE Standard 55 [4] limits the use of the adaptive comfort model exclusively to NV buildings where no mechanical cooling system is installed. This means that MM buildings should be treated as AC buildings and operated as per the air conditioning comfort zone (calculated with the PMV-PPD model) even when the building is operating in naturally-ventilated mode. Since its inclusion in ASHRAE Standard 55-2004, a relaxed thermal comfort zone promoted by the adaptive model has permitted design and operational approaches to rely more on passive strategies, contributing to the reduction of energy used for space heating and cooling in the building sector [15]. Notwithstanding the profound energy implications, ASHRAE Standard 55's explicit restriction on the adaptive model's scope of application has restricted the uptake of energy-efficient mixed mode approaches.

Previous research in this domain finds that the mode of operation can affect users' comfort responses [16] even when indoor conditions are identical [17]. There is also a recommendation for the adaptive comfort model to be applicable during NV mode of operation in MM buildings [17,18]. However, more research seems necessary to be able to reach a consensus regarding which comfort model is most appropriate for different operational modes in MM and better understand how they influence occupant comfort. This paper specifically addresses how AC and NV modes in a mixed-mode building can affect indoor environmental conditions, occupants' perception of thermal comfort and their adaptive comfort behaviours.

The international research community has recently been focusing on fundamental questions about the underlying mechanisms of adaptive thermal comfort in buildings. From 2015 through 2019 a global network of thermal comfort researchers have been coordinating through the International Energy Agency's Energy in Buildings and Community Programme (IEA-EBC) Annex 69 – *“Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings”*. The ultimate objective of the Annex is to reduce energy use across the building sector without compromising occupant comfort through the application of the adaptive concept in design, evaluation and control of indoor environments. One of the key research activities of Annex 69 is to conduct case studies of office buildings in participating countries, focusing on the best practices of building performance in both occupant comfort and energy efficiency. This paper reports the key findings from an IEA Annex 69 case study mixed-mode building located in Australia.

2. Methods

2.1 Climatic setting of the case study building

The case-study mixed-mode building for this project is located in Wollongong, a satellite city of Sydney Australia. The building is situated at Latitude 35°S and within 1 km of the Pacific Ocean, explaining the humid subtropical climate (Cfa in the Köppen climate classification). Winters are mild and

temperate, and summers are warm and humid. The Australian Bureau of Meteorology recorded a mean daily maximum temperature in Wollongong during the monitoring period of 21.5°C. The mean daily minimum temperature reported for the study period was 14.9°C.

2.2 The case study building

The case study building in this project is the Sustainable Buildings Research Centre (SBRC), a 6 Star Green Star building located on the University of Wollongong Innovation Campus. The Green Star accreditation framework was introduced in 2003 by the Green Building Council of Australia and is used nationally to rate building sustainability on a scale ranging from 1 to 6 Stars, with 6 Stars being the highest possible score. In addition, the SBRC was designed to meet the stringent requirements of the Living Building Challenge sustainability framework developed by the International Living Future Institute, and is the first building in Australia to win net-zero energy and 'petal' accreditation under this scheme. The building accommodates university academics, technical and administrative support staff, and postgraduate research personnel. The main aim of the SBRC research team is to meet the challenge of improving energy efficiency throughout our built environment and making new and existing buildings more sustainable.

The SBRC is a net-positive energy building comprising a number of office and laboratory areas, which is powered entirely by electricity. The 160 kWp photovoltaic solar array on the roof of the SBRC generates approximately 240 MWh/yr of renewable electrical energy, while the electricity consumption of the building as a whole amounts to approximately 140 MWh/yr, which is 8 MWh/yr less than the design target. The total energy consumption was designed to be less than one third of that for similar conventional buildings at the time of construction. The actual annual electrical energy demand of the HVAC system has been metered as approximately 48 MWh/yr. A centralised BMS is used to control the zoned mixed-mode HVAC system based on occupancy and indoor/outdoor conditions as shown in Fig. 1. Natural ventilation can only be used if the outdoor wind velocity does not exceed 30 km/h. Information on the outdoor conditions are provided by a weather station to the BMS. For the entire duration of this study the building was operated as a mixed-mode open-plan office typical for the Sydney-Wollongong region.

Natural ventilation is delivered through operable windows controlled by BMS-connected electrical actuators. When the building is operating in air conditioned mode the conditioned air is delivered to occupied zones of the main office area via swirl diffusers set in the thermally activated floor slab. To further improve perceived comfort and satisfaction the SBRC building is designed to afford its occupants a variety of adaptive opportunities, including manual override of the operable windows, portable pedestal fans, in addition to the adjustable floor-mounted swirl diffusers. Furthermore, occupants of this building are not required to adhere to any dress code and are indeed encouraged to adapt their clothing to prevailing weather and seasonal conditions. The SBRC building accommodates university academics, technical and administrative support staff, and postgraduate research personnel.

Fig. 1. Mixed-mode ventilation system control logic (as a function of indoor and outdoor air temperatures at the time of operation) adopted in the surveyed building (AC-C = AC Cooling; AC-H = AC Heating; NV = Natural Ventilation) [image size: Single Column Fitting]

2.3 Collecting objective data: instrumental monitoring

Longitudinal survey observations were made in the office spaces of the SBRC building between June 2017 and April 2018, capturing the building's indoor environmental quality (IEQ) performance during winter, swing, and summer seasons. Autonomous monitoring stations known as SAMBA were placed at various sampling points throughout the regularly occupied zones of the building (Fig. 2). SAMBA is a pervasive and continuous IEQ monitoring system enabling the collection of high spatio-temporal resolution data [19]. Detailed information on the specifications and calibration performance of the IEQ sensors built in the SAMBA can be found in Parkinson et al. [20]. In our sample building, SAMBA stations monitored and averaged indoor environmental parameters at 5-minute intervals (time-stamped). The collected data were transmitted through the cellular network to the University of Sydney IEQ Lab's file-server. Hourly outdoor meteorological observations were acquired from the Bureau of Meteorology's automatic weather station closest to the SBRC. Time-stamped building operational status details including HVAC and NV modes, occupancy schedules and window status were retrieved from the BMS retrospectively. Time-stamps on IEQ, BMS and meteorological data enabled pairing of all data streams for subsequent analysis.

Fig. 2. Office areas of the sample building (left) and indoor climate measurements using a bespoke IEQ data acquisition system (SAMBA) unit placed on a workstation (right) [image size: 1.5 Column Fitting]

2.4 Collecting subjective data: right-here-right-now survey

A customised right-here-right-now (RHRN) survey was employed to collect subjective comfort evaluations from SBRC building occupants throughout the 11-month monitoring period. Out of a total building population of 50 staff, 31 occupants agreed to participate in this study. Being a longitudinal research design, the participants were required to respond to our online comfort survey on multiple occasions over the 11-month monitoring period. Each participant received cell-phone text messages containing a web link to the online RHRN comfort questionnaire [21]. SMS invitations were sent out periodically, with a frequency of approximately 1 to 3 times per week during normal occupied hours. The questionnaire was designed to require less than one minute to complete, and addressed simple questions; (1) whether or not the participant is in the building at the time of the survey, (2) their location within the building when completing the survey, (3) their RHRN thermal comfort perception (i.e. sensation, preference and acceptability), (4) the kinds of adaptive comfort behavioural strategies in use, and (5) a simple check-list of behavioural activity and clothing being worn to allow for estimates of metabolic rate and clothing insulation. Each of the survey responses was time-stamped at the point when the questionnaire was completed to enable pairing with other data streams described in Section 2.3. The smartphone RHRN comfort questionnaire used in the study is summarised in Table 1. A total of 909 full sets of data resulted from this procedure and are used for the analysis presented in subsequent sections of this paper.

Table 1 Summary of the online questionnaire

Question	Answer
Are you currently in SBRC building?	- Yes - No (survey terminates)
Where are you right now?	- Open office, east - Open office, west - Cubicle, east

How do you feel, right here right now?	<ul style="list-style-type: none"> - Cubicle, west - Flexi office - Cold - Cool - Slightly cool - Neutral - Slightly warm - Warm - Hot
Here and now, would you prefer to be	<ul style="list-style-type: none"> - Cooler - No change - Warmer
Is this thermal environment acceptable?	<ul style="list-style-type: none"> - Yes - No
Which comfort strategies are in use, here and now?	<ul style="list-style-type: none"> - Adjust clothing - Use personal fan - Use personal heating - Adjust floor diffuser - Consume hot/cold beverages or food - Override BMS to open window
Which best describes your clothing right now? ^a	<ul style="list-style-type: none"> - Very light (0.4 <i>clo</i>) - Light (0.5 <i>clo</i>) - Slightly light (0.6 <i>clo</i>) - Slightly heavy (0.9 <i>clo</i>) - Heavy (1.0 <i>clo</i>) - Very heavy (1.4 <i>clo</i>)
Which best describes your activity during the preceding half hour? ^b	<ul style="list-style-type: none"> - Relaxing, seated (1.0 <i>met</i>) - Working, seated (1.1 <i>met</i>) - Working, standing (1.4 <i>met</i>) - Walking about (1.7 <i>met</i>) - Exercising (3.0 <i>met</i>)

^{a,b} Clothing and activity descriptions were given as pictograms in the online survey questionnaire

3. Results

3.1 Outdoor conditions

Fig. 3 depicts daily outdoor temperature during the field-monitoring period. Based on daily minimum and maximum temperature records obtained from the closest *Bureau of Meteorology* station, daily mean temperatures and 7-day running mean temperatures were calculated and included in this figure. The average of daily mean outdoor temperatures in winter and in summer during the monitoring period were 14.3 and 22.2°C respectively. As can be seen in Fig. 3, the outdoor maximum temperature occasionally exceeded 35°C across the summer monitoring period.

Fig. 3. Daily outdoor temperatures (°C) for Wollongong during the field study period (data obtained from Australian Bureau of Meteorology) [image size: Single Column Fitting]

3.2 Indoor conditions

A total of over 140,000 five-minute averages of the IEQ parameters measured by SAMBA devices during normal occupied hours (9am-5pm working days, excluding weekends and holidays) were used for the present analysis. In order to broadly characterise the patterns of indoor environmental conditions under the building's different mixed mode operational modes, these data were categorised by building mode – i.e. AC-Cooling (AC-C), AC-Heating (AC-H), and Natural Ventilation (NV). Fig. 4 summarises how the building performed on the key IEQ parameters, namely operative temperature (T_o), air speed (V_{air}), Predicted Mean Vote (PMV), and carbon dioxide concentration (CO_2). The clo -values used to calculate PMV in Fig. 4 were estimated using the ASHRAE 55 standard's clothing insulation model (i.e. the clo for a day as a function of outdoor air temperature at 6AM) instead of the RHRN comfort questionnaire clothing checklist because the latter was only available at times when occupants responded to the RHRN smartphone questionnaire. A standard office activity (met of 1.1) was assumed in these PMV calculations for the same reason. Overall, the indoor operative temperatures were slightly higher in AC-C mode and slightly cooler in AC-H mode, compared to NV mode. This reflects a typical characteristic of the mixed-mode operation in which the building operates in NV mode only when external conditions are favourable, whereas the building is in heating/cooling mode during cold/hot days respectively. Air speeds (m/s) within the occupied zones were generally higher when the building was in NV mode (windows open) compared to AC modes.

Fig. 4 includes the compliance time based upon PMV calculations and CO_2 measurements, expressed as % of occupied hours during which the PMV or CO_2 was compliant with the recommended target thresholds. In the current analysis, the PMV performance thresholds of ± 0.5 [4] and CO_2 threshold of 1000 ppm [22] were applied. The compliance time was low in AC-C (63.1%) and AC-H (43.3%) modes, whereas during the NV operation over 81% of occupied time fell within the target range ($-0.5 < PMV < +0.5$). It should be noted that the PMV index's two personal input parameters (i.e. *met* and

clo) used in these calculations might not precisely represent our actual values for the sample, which is discussed in the later sections. Indoor CO₂ concentrations were lower in NV mode than AC modes, but consistently well below the upper threshold limit of 1000ppm regardless of the building's mode of operation.

Fig. 4. Patterns of indoor environmental parameters during occupied hours in different building operation modes i.e. Natural Ventilation (NV), AC-Cooling (AC-C) and AC-Heating (AC-H); $n=143,737$. The red and blue line in the two graphs on the right shows the upper and lower threshold for PMV and CO₂ concentrations, respectively. [image size: 1.5 Column Fitting]

Fig. 5 and Fig. 6 illustrate the building's thermal performance in the two ventilation modes (NV or AC). Fig. 5 plots indoor operative temperatures (T_o) against the ASHRAE Standard 55 adaptive model's 80% acceptability range. In Fig. 5, only those data points collected when the building was operating in NV mode are included. For approximately 99% of the time indoor T_o measurements were within the adaptive comfort standard's 80% acceptability limits. In Fig. 6, the instrumental data collected when the building was in the air-conditioning mode (AC-C or AC-H) are plotted against the PMV model's comfort zone in ASHRAE Standard 55. In AC-Heating mode, T_o observations were often on the cold side of the comfort zone. For approximately 17% of the occupied time, T_o fell below the lower limit of winter comfort zone (i.e. 1 *clo* zone). In AC-Cooling mode, a significant amount of data fell beyond the lower- and upper threshold of the summer comfort zone (i.e. 0.5 *clo* zone). This could be explained by the fact that for the entire duration of this study the BMS system did not always operate in compliance with the design intentions. During post-occupancy some technical malfunctions in the BMS system were identified, which led to IEQ conditions occasionally straying beyond design specifications.

Fig. 5. Indoor operative temperature (T_o) records during NV operation (occupied time), plotted against the ASHRAE Standard 55 adaptive comfort zone [image size: Single Column Fitting]

Fig. 6. Monitored indoor conditions during AC operation (occupied time), plotted against the ASHRAE Standard 55 psychrometric chart [image size: Single Column Fitting]

3.3 Right Here Right Now Comfort Survey

Descriptive statistics including the range, mean, and standard deviation of each comfort parameter measured/calculated at the time when each smartphone questionnaire was completed are presented in Table 2. The indoor operative temperature varied between 18.5 and 29.9°C. The range of self-reported *clo*-value (0.4~1.4 *clo*) indicated that the participants were flexible in their choice of clothing.

Participants were mostly sedentary and engaged in typical office activities during the time of survey completion. Their mean metabolic rate (*met*) was 1.3. On average, the PMV (using the self-reported *clo* and *met* as the input variables) was 0 (neutral), and the Predicted Percentage of Dissatisfied (PPD) index estimated that just over 11% of survey participants would be dissatisfied with the indoor thermal environment prevailing at the time of the questionnaire. The actual Thermal Sensation Vote (TSV) of the participants was very closely aligned (mean TSV = 0.1) with the predicted value (PMV = 0).

Table 2 Summary of indoor climate and thermal comfort indices recorded at survey times ($n=909$)

Indices	Min.	Max.	Mean	Std. Deviation
T_o (°C)	18.5	29.9	23.9	1.7
RH (%)	17	78	53	13
V_{air} (m/s)	0.01	0.56	0.08	0.05
<i>clo</i>	0.4	1.4	0.6	0.2
<i>met</i>	1.0	3.0	1.3	0.2
PMV	-1.9	+2.4	0.0	0.6
PPD	5.0	89.7	11.6	10.6
TSV	-3	+3	0.1	1.0

Percentage breakdowns of the participants' thermal comfort perception recorded via smartphone questionnaire are summarised in Table 3. PMV values calculated for each sample were rounded up/down to the closet point on the 7-point thermal sensation scale, and the distribution added into this table for comparative purposes. It is typically assumed that votes in the middle three categories of the 7-point thermal sensation scale are expression of thermal satisfaction (i.e. *slightly cool* -1, *neutral* 0, *slightly warm* +1) [23]. Applying this assumption to the current subjective data, 86.7% of the occupants expressed satisfaction with the building's thermal environment. This satisfaction rate was also well aligned with the thermal acceptability (88.9%) as registered directly in the comfort questionnaire (Table 1). However, there was about 13% discrepancy between the actual (85.7%, according to the TSV distribution) and the predicted value (98.6% according to the PMV distribution), which is further investigated in the subsequent section of this paper.

Table 3 Summary of indoor climate and thermal comfort indices recorded at survey times ($n=909$)

Comfort indices	Rating scale	Percentage
Thermal Sensation Vote (TSV)	- Cold (-3)	1.2%
	- Cool (-2)	1.9%
	- Slightly cool (-1)	15.4%
	- Neutral (0)	56.3%
	- Slightly warm (+1)	14.0%
	- Warm (+2)	5.5%
	- Hot (+3)	2.4%
Thermal Preference (TP)	- Cooler	16.4%
	- No change	66.7%

Thermal Acceptability (TA)	- Warmer	16.9%
	- Acceptable	88.9%
	- Unacceptable	11.1%
Predicted Mean Vote (PMV)	- Cold (-3)	0%
	- Cool (-2)	0.2%
	- Slightly cool (-1)	19.6%
	- Neutral (0)	64.9%
	- Slightly warm (+1)	14.1%
	- Warm (+2)	1.2%
	- Hot (+3)	0%

A subset of the RHRN survey dataset which included only those responses collected when the building was operating in AC mode is presented in Fig. 7. When the participants were exposed to indoor climatic conditions warmer than the upper threshold of the 0.5 *clo* comfort zone, the majority of them felt ‘slightly warm’ or ‘warm’. Some ‘cold’ votes were registered even though the indoor condition fell within the 1.0 *clo* comfort zone. Fig. 8 shows another subset of the RHRN survey data recorded when HVAC was turned off, i.e. in NV mode. In Fig. 8, survey responses recorded during the NV operation were plotted against the adaptive model comfort region. The number of participants registering ‘warmer-than-neutral’ sensations increased as T_o exceeded about 24~25 °C. Some ‘cold’ sensations were observed as T_o dropped below 23°C.

Fig. 7. Thermal Sensation Votes (TSVs) during AC operation, plotted against the psychrometric chart
[image size: Single Column Fitting]

Fig. 8. Thermal Sensation Votes (TSVs) during NV operation, plotted against the ASHRAE Standard 55 adaptive comfort zone [image size: Single Column Fitting]

3.4 Predicted (PMV) vs. actual (TSV) thermal sensation

The discrepancy between the actual (TSV) and predicted (PMV) thermal sensations observed in Table 3 was further investigated by fitting a linear regression between the two variables. In the current analysis our longitudinal survey data was treated as if it was 'transverse', based on an assumption accepted across thermal comfort researcher community that within-subject variability in subjective comfort responses is as large as between-subject variability [24]. The entire data set was grouped according to the operational mode of the building at the time each questionnaire was completed; AC mode ($n = 416$) and NV mode ($n = 461$). The relationship between TSV and PMV is shown in Fig. 9, and the results of regression analysis are given in Eq. 1 and Eq. 2. In Fig. 9 the samples are binned at 0.5 sensation vote intervals along the rating scale for illustration purposes only (Eq. 1 and Eq. 2 are based on experimental unbinned data). Theoretically the regression model should have a coefficient (gradient) of unity and a y-intercept of 0. When this mixed-mode building was operating in AC mode, the participants' TSV conformed to the PMV values relatively well, with a regression coefficient of 0.85. However, a large discrepancy was observed when the building was in NV mode. According to Eq. 2, a shift of one unit in PMV corresponds to only a 0.59 unit change in TSV.

Fig. 9. Thermal Sensation Votes (TSV) regressed on Predicted Mean Votes (PMV), categorised by building operation mode (AC vs. NV). The size of circle is proportional to the number of samples. [image size: Single Column Fitting]

$$\text{TSV} = 0.85 \times \text{PMV} + 0.15 \text{ (AC mode; } n = 416; R^2 = 0.26; \text{ regression coefficient } p < 0.001) \quad (1)$$

$$\text{TSV} = 0.59 \times \text{PMV} + 0.02 \text{ (NV mode; } n = 461; R^2 = 0.12; \text{ regression coefficient } p < 0.001) \quad (2)$$

While it accounts for all the basic comfort heat-balance parameters, the preceding analysis (Fig. 9) ignores thermal adaptation processes that might have played a role in shaping the participants' perception of comfort over the period of the field monitoring. According to the fundamental concept of the adaptive model, the perception of thermal comfort is affected by past and current thermal experiences [25]. Given that this longitudinal research design spanned different seasons, it is reasonable to assume that adaptive processes affected the comfort responses of our survey participants.

In the next analysis, a relative temperature scale (temperature offset from neutrality, T_{diff}) was used to adjust for adaptive processes within each of the samples (e.g. [26,27]). The temperature difference between indoor operative temperature T_o at a point in time and the predicted adaptive neutral temperature T_n (calculated by ASHRAE 55 adaptive model: $T_n = 0.31 \times \text{prevailing mean outdoor temperature} + 17.8$) was calculated for each of our samples (i.e. $T_{\text{diff}} = T_o - T_n$). Therefore, positive values of T_{diff} represent indoor thermal conditions in which T_o was *warmer* than the adaptive model's neutrality, whereas negative values indicate T_o was *cooler* than T_n . In order to investigate how the participants' thermal sensations changed across different indoor temperature exposures, a linear regression was fitted between TSVs and T_{diff} .

The regression model performed separately on the two sub-samples (AC and NV mode) are presented in Fig. 10, Eq. 3 and Eq. 4. Again, the data is binned at half-degree intervals only for graphical clarity in Fig. 10. The ASHRAE 55 adaptive model almost perfectly estimated the neutrality of our participants (by examining the point of intersections between the regression lines and TSV of 0 in Fig. 10). The slope of the regression lines can be interpreted as thermal sensitivity of occupants. For example, a steep slope indicates that the participants were sensitive to temperature variations and a gentle slope indicates that the participants are highly adaptive to or tolerant of changes in their indoor thermal environment. The results presented in Fig. 10 suggest that occupants were about 30% more tolerant of indoor temperature variations when the building was operated in naturally-ventilated mode compared to air-conditioned mode. In this analysis, the 80% acceptability range can be defined by a mean TSV = ± 0.85 (based on the precedent of PPD=20% when PMV equals ± 0.85). Using Eq. 3 and Eq. 4, the temperature range corresponding to a group mean TSV is derived to be 4K for the AC group and 6K for the NV group.

Fig. 10. Thermal Sensation Votes (TSV) regressed on indoor temperature variations, categorised by building operation mode (AC vs. NV). The size of circle is proportional to the number of samples. [image size: Single Column Fitting]

$$\text{TSV} = 0.39 \times T_{\text{diff}} - 0.01 \text{ (AC mode; } n = 416; R^2 = 0.29; p < 0.001) \quad (3)$$

$$\text{TSV} = 0.28 \times T_{\text{diff}} + 0.02 \text{ (NV mode; } n = 461; R^2 = 0.15; p < 0.001) \quad (4)$$

3.5 Adaptive behaviour: clothing adjustment

Table 4 presents the percentage breakdown of the participants' adaptive behaviours registered through the RHRN surveys. The most frequently reported adaptive behaviour in this mixed-mode building was clothing adjustment (62.4%), followed by consumption of beverages/food (25.1%). The other adaptive opportunities addressed in the questionnaire such as 'use fan', 'use personal heating', 'adjust diffuser', and 'override BMS to open window' were not frequently observed, each registering less than 5% of the total votes. It should be noted that the online questionnaire did not include an option for those who didn't initiate any adaptive strategies (i.e. N/A) and it's likely that they resorted to the first option 'Adjust clothing'. Therefore it's reasonable to speculate that the frequency of clothing adjustment reported in Table 4 is over-estimated.

Table 4 Percentage breakdown of thermal adaptation comfort behaviours at the time of the RHRN survey

Adaptation strategy	Percentage (%)
- Adjust clothing	62.4%
- Consume hot/cold beverages or food	25.1%
- Use personal fan	4.1%
- Use personal heating	4.0%
- Adjust floor diffuser	2.7%
- Override BMS to open window	1.9%

Fig. 11. Comparison between the ASHRAE 55 clothing insulation model and the *clo* values observed in the present study. The size of circle is proportional to the number of samples [image size: Single Column Fitting]

ASHRAE Standard 55 [4] presents a clothing insulation (*clo*) prediction model based on the observed outdoor air temperature at 6AM, T_{out6AM} that day. This model was originally developed by Schiavon and Lee [28] based on a meta-analysis of the ASHRAE RP-884 and RP-921 thermal comfort databases. According to this predictive model, the clothing insulation of a typical occupant for a day in which T_{out6AM} falls between 5 and 26°C is determined as: $clo = 0.6863e^{-0.0152T_{out6AM}}$. The clothing insulation data collected with our RHRN questionnaires in a mixed-mode building (Table 1) was then compared against the ASHRAE *clo* model's predictions. During the survey period, T_{out6AM} in Wollongong, where the sample building is located, always fell within the range of 5 and 26°C. The observed *clo*-values were related to T_{out6AM} , and plotted against the ASHRAE *clo* model's predictions in Fig. 11. The *clo* data in this figure were binned into 1°C intervals for illustrative clarity. It was found that the ASHRAE *clo* model underestimated the *clo* value when T_{out6AM} was below 18°C, and overestimated the *clo* value when T_{out6AM} was over 18°C. The regression model fitted to the present study data (unbinned) is defined as:

$$\text{For } 5^{\circ}\text{C} \leq T_{out6AM} < 26^{\circ}\text{C}, clo = 1.262e^{-0.0489T_{out6AM}} \quad (R^2 = 0.33) \quad (5)$$

The current analysis used T_{out6AM} as the predictor to maintain direct compatibility with the ASHRAE model. Outdoor air temperature at 6AM (T_{out6AM}) is deemed as a good approximation of the daily minimum air temperature (T_{outMIN}). However, we observed up to a few degrees (°C) of discrepancy between T_{out6AM} and T_{outMIN} in our sample. When we used daily minimum air temperature, the predictive model improved with an increased R^2 value, which is described in Eq. 6 below.

$$\text{For } 5^{\circ}\text{C} \leq T_{outMIN} < 26^{\circ}\text{C}, clo = 1.24e^{-0.0501T_{outMIN}} \quad (R^2 = 0.37) \quad (6)$$

4. Discussion

Continuous monitoring of the indoor environment indicated that the operational characteristics of the mixed-mode building were considerably different to those observed in conventionally air-conditioned buildings in which a narrow temperature dead-band is maintained (e.g.[3]). As seen in Fig. 6, even when the sample building was in air-conditioning mode, the indoor operative temperature range tended to stretch well beyond the comfort zone recommended in the relevant standards for air-conditioned spaces. The indoor thermal condition of the sample building was close to 'slightly cool' condition, particularly during AC-Heating mode (Fig. 4). A significant proportion of occupied hours fell outside the prescribed comfort zone, yet the occupant responses on the RHRN questionnaires showed a very high level (almost 90%) of thermal acceptability (Table 3). This indicates that the building was successful in delivering 'satisfactory' indoor thermal conditions to its occupants despite frequent excursions beyond the industry-standard 80% acceptability target. Before further generalising this result, it should be cautioned that although our RHRN surveys ($n=909$) were despatched randomly they might not have accurately represented the indoor conditions characterised by the physical measurements ($n=143,737$). In fact, indoor thermal conditions in some cold mornings were under-represented in the RHRN survey data (comparing Fig. 6 with Fig. 7). Nevertheless, our participants seemed to know how to restore thermal comfort through behavioural adjustment. Furthermore, we observed a very wide range of mean *clo*-values (0.4-0.8), much wider than predicted by the ASHRAE 55's clothing insulation model (0.46-0.63) for the outdoor temperatures observed during this field study (Fig. 11). In effect, the occupants of this mixed-mode building demonstrated much more weather-sensitivity in their clothing behaviour than predicted by the ASHRAE Standard 55 clothing insulation (*clo*) prediction model, especially on days when colder outdoor temperatures were registered. They wore 0.1~0.2 more *clo* than predicted by the clothing model in ASHRAE Standard 55.

Although it falls beyond our investigation, the demographic characteristics of our participants might have played a role in achieving a high level of satisfaction in the surveyed building. It is known that there is possible association between occupant satisfaction and environmental attitudes or expectations. For example, an earlier Australian study carried out in almost the same context (i.e. academic office building in sub-tropical climate) found that 'green' occupants (i.e. those who have higher levels of environmental concern) were more forgiving of their building than their counterparts [29]. Given that some of our participants were engaged in building sustainability research, it is reasonable to speculate that they understood how the building's mixed-mode operation was supposed to work, and were already prepared to accept indoor thermal variations observed during the survey period.

It has previously been reported in the literature that the mode of operation (i.e. AC vs. NV) in mixed-mode buildings can affect occupants' subjective perception of indoor thermal environment [17,18] over and above the effects of indoor climatic conditions in the two modes. The results of our analyses (Fig. 9 and 10) highlight discrepancies between the actual and predicted comfort level of occupants in mixed-mode buildings, especially during NV mode. Fundamental differences between the two different modes of building operation revealed in Fig. 9 and 10 reinforce the earlier published findings. The occupants' actual thermal sensations changed about 40% less than predicted by the PMV model when this mixed-

mode building operated in NV mode (Fig. 9). According to adaptive thermal comfort theory, the gradient of the regression equation (Eq. 3 and 4) is inversely proportional to the occupants' adaptability. The discrepancy between the two regression coefficients in Eq. 3 and Eq. 4 indicates that the thermal adaptability of the same group of occupants varies depending on the ventilation mode in operation. According to Eq. 3, a change of indoor temperature of 2.6 degrees accounts for one unit change of thermal sensation when the building is operating in AC mode, whereas in NV mode it requires 3.6 degrees of temperature change to shift up/down thermal sensation by one unit (Eq. 4). In effect these building occupants were more successfully maintaining comfort for themselves and adapting to the indoor thermal conditions during the building's NV operation mode compared to the AC period. Moreover, the NV mode sample's regression coefficient of 0.28 in this mixed-mode building was virtually identical to the mean regression gradient of 0.27 observed in the NV building samples of the ASHRAE RP-884 project [8]. The latter forms the basis of ASHRAE Standard 55's adaptive comfort model, suggesting that during the NV operation in our MM building, the occupants' thermal comfort responses closely resembled those observed in full-time NV buildings with no mechanical conditioning system at all. On the other hand, the AC sample group's regression coefficient of 0.39 was smaller than that of 0.51 observed in the AC building samples of the ASHRAE RP-884 project [8]. In other words, during the AC operation in the studied mixed-mode building the occupants' perceptions of the indoor thermal environment fell somewhere between those of occupants of AC building and NV buildings – being less adaptive than those in NV buildings but more adaptive than those in AC buildings. In the current ASHRAE Standard 55 [4] the application of the adaptive comfort model is strictly limited to full-time naturally ventilated spaces where no mechanical conditioning system is installed. This means that MM buildings are excluded from the scope of the adaptive comfort standard even during the NV operation period. However, the analysis in this paper provides compelling empirical evidence that, from the perspective of occupant thermal comfort, MM buildings can be classified as NV at least during the NV operation period. Therefore our results imply that a relaxed thermal comfort zone promoted by the adaptive model can permit design and operational approaches for MM buildings to rely more on passive strategies, which will lead to the reduction of energy used for space heating and cooling.

There is further optimisation potential by employing adaptive comfort principles, which suggest that the acceptable range of indoor temperatures drifts in sync with the outdoor seasonal cycle – shifting up in warm weather and down in cool weather. The operational mode of the surveyed building was purely determined as a function of indoor and outdoor temperatures, regardless of seasonal weather variations. Thus, defining a seasonally appropriate 'moving target' during the NV operation period [30] and implementing it in the BMS control logic will allow the building to move more aggressively towards more efficient operation.

5. Conclusion

As part of IEA-EBC Annex 69, a longitudinal field study was conducted focusing on thermal comfort in a mixed-mode building. Time-and-place matching of multi-dimensional data (i.e. smartphone survey responses, instrumentally measured indoor climate parameters, outdoor meteorological observations, and building operational information) enabled quantitative analysis of the relationships between those parameters. The key findings of this Australian case-study conducted in the mixed-mode context can be summarised as follows:

- Despite of a wide range of indoor thermal conditions observed during the longitudinal monitoring, the studied mixed-mode building successfully delivered a high level of thermal comfort. The result contradicts a widely held misconception in facilities management practices that a tight control of indoor temperature equates to a high level of occupant comfort.
- The occupants' response to indoor thermal environments differed between the two modes of building operation – i.e. air-conditioning (AC) and natural ventilation (NV). The occupants were more tolerant of, or adaptive to indoor temperature variations during the NV operation period than the AC period.
- The occupants in the studied building more actively adjusted their clothing insulation than that predicted by the ASHRAE 55's dynamic clothing insulation model. The ASHRAE model tended to underestimate the *clo*-value especially in cold temperature conditions.
- The empirical findings support that the adaptive comfort standard is suitable to MM buildings especially during the NV operation period.

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