Field Study of Air Conditioning and Thermal Comfort in Residential Buildings

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Abstract
The aim of this study is to better understand the external and internal drivers that affect residential air-conditioning (A/C) use decisions and occupant comfort. Field observations were carried out using instrumental measurements and smartphone questionnaires, recording householder’s A/C usage patterns, indoor/outdoor climatic factors, perception of thermal comfort and adaptive behaviours. Throughout the 2-year monitoring period, a total of 4,867 A/C use events and 2,105 online comfort questionnaires were collected from 42 homes in Australia. The householders’ neutral temperature was estimated to be 2 degrees lower than that predicted by the ASHRAE 55’s adaptive model. Despite the lower-than-expected neutrality, comfort zone widths for 80\% acceptability were found to be 9K in residential settings, which is 2K wider than that expected by the adaptive model. Our findings indicated that people in their homes are more adaptive to, and tolerant of significantly wider temperature variations than expected (in particular cooler temperature conditions). Based on the analysis of the results, an adaptive model that can be used for the assessment of residential thermal comfort is proposed in this paper. This study also revealed the householders’ thermal adaptation behaviours as a function of temperature variations, which can be utilised in building energy modelling softwares.

Keywords: Thermal comfort, Air conditioning, Residential building, Adaptive model, Comfort zone

1 Introduction
The current international standards on human thermal comfort, such as ASHRAE Standard 55 (ASHRAE, 2013) and ISO 7730 (ISO, 2005), are regarded as universally applicable to all types of indoor spaces. These standards were originally intended to provide guidelines for centrally controlled HVAC systems, based on human heat-balance model exclusively derived from climate chamber experiments. The broad applicability of heat-balance model to real-world settings has been challenged by a number of field studies based on the theory of occupant thermal adaptation in which perception of comfort is affected by contextual factors such as outdoor climate, thermal history and expectations (e.g. Auliciems, 1981; Humphreys, 1978; Humphreys and Nicol, 2002). The adaptive comfort model, derived from empirical evidences quantifying the dependence of comfort zone on outdoor weather (de Dear and Brager, 2002), has been incorporated in the current ASHRAE Standard 55-2013 for naturally-ventilated spaces as an alternative to the heat-balance model. In adaptive hypothesis, occupants interact with the surrounding environment with a certain degree of control to achieve comfort, rather than just being passive recipients of the given thermal
environment (Brager and de Dear, 1998). Therefore ‘adaptive approach’ is expected to adequately reflect human comfort in residential settings where occupants play an active role, by adjusting their behaviours or even modifying the surrounding environment to make themselves more comfortable. Nevertheless, whether the comfort zone defined by the ASHRAE 55’s adaptive comfort standard can be directly applied to the residential context is somewhat questionable as the empirical data (i.e. ASHRAE RP-884 database) that formed the basis of the adaptive model was mainly from office buildings (de Dear, 1998), where occupants’ activities and their control over the environment are relatively restricted, compared to their homes, mostly likely due to the shared use of space and organisational culture. On the other hand, in homes occupants are engaged in much more diverse activates, and have greater degree of adaptive opportunities and a higher level of perceived control (Hwang et al., 2009; Karjalainen, 2009). Given that the perceived degree of control is known to be one of the strongest predictor of thermal comfort (Leaman and Bordass, 1999; Paciuk 1990), home residents’ comfort zone should be wider than that of office workers due to greater degree of adaptive opportunities as previously conceptualised by Baker and Standeven (1996).

Previous comfort studies conducted in residential settings have shown systematic discrepancies between the actual comfort level reported by occupants and the predicted by the comfort standards: such as neutralities lower than predicted by the PMV model (Feriadi and Wong, 2004; Hwang et al., 2009; Oseland, 1995), the PMV model’s overestimation of the percentage of dissatisfied (Becker and Paciuk 2009; Han et al. 2007), and residents showing greater adaptability or tolerance than suggested by the adaptive model (Wang, 2006; Ye et al., 2006). The most compelling explanations for these discrepancies are contextual factors influencing occupant thermal perceptual processes in homes: including greater adaptive opportunities, greater control over the environment, more flexible clothing patterns, more diverse activities, or energy price affecting consumer patterns.

Despite air-conditioning (A/C) having become one of the fastest growing end-uses of electricity in Australian homes, there has never been a rigorous investigation into the occupant A/C use patterns, adaptive behaviours and perception of thermal comfort in residential contexts. Over a century of thermal comfort research activities worldwide, studies focused on residential environments are rare (e.g. Daniel et al., 2014; Lomas and Kane, 2013; Rijal et al., 2013) while overwhelming majority of them were based on office settings. The most likely reason for residential comfort being understudied is the difficulties in logistics. While researchers can collect objective and subjective comfort evaluations from a concentrated sample of occupants in office buildings, peoples’ homes are geographically dispersed and there are potential issues with long-term installation of equipment and concerns of householder privacy.

This paper presents the results of a longitudinal field studies carried out in Australian homes for over a period of two years, with a focus on better understanding the external and internal drivers that affect householders’ A/C use decisions, adaptive behaviours and thermal comfort. To test our hypothesis that greater adaptive opportunities in homes can result in a wider range of comfort zone, statistical analysis is performed to develop an adaptive model defining the comfort zone of householders. Our empirical finding is then compared with the ASHRAE 55’s adaptive comfort standard and implications are discussed.
2 Methods

A total of 42 homes were recruited in Sydney (27 homes) and Wollongong (15 homes) for questionnaire surveys and instrumental monitoring. Only those homes equipped with at least one A/C unit were included in our field study. Field observations were made for two years (March 2012 ~ March 2014), focusing on; (1) each household’s air-conditioning usage, (2) external climatic drivers of usage patterns, (3) internal factors influencing perceptions of thermal comfort, and (4) actual householders’ perceptions of thermal comfort and related behaviours.

During the first site-visit researchers administered a background survey of household demographics, housing characteristics and air-conditioning appliances characteristics. Indoor air temperature and humidity monitoring devices, iButtons, were also installed in various locations in the occupied zone of the participants’ homes (such as living room, bedroom, dining room, kitchen, study, etc.), recording indoor air temperature and humidity every 15 minutes. An iButton was also placed directly into the supply air path of the air conditioner or fan-coil unit, which enabled researchers to investigate when and where A/C units were used.

An Excel macro was developed to detect sudden changes in the A/C supply air temperature and then compare it to the temperature in the occupied zone to determine the A/C operation mode being used. First, if the difference between two contiguous supply air temperature measurements was greater than 3.5°C then the A/C was considered to be switched on within that 15-minute period. The temperature in the occupied zone when the A/C was operational and two subsequent measurements (three total) were then analysed; the decision to use three measurements was made in consideration of temperature cycling. If the difference between the maximum of the three temperatures in the occupied zone and the supply air temperature was greater than the threshold specified for that house (nominally 3°C but changed to suit individual cases) then heating was being used. If not, the same logic was applied to the minimum of the three measurements to test if cooling was being used. This logic was continued until neither case was true and then the A/C was

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**Fig. 1 Screenshots of the smartphone comfort questionnaire**
labelled as off. Extensive testing of the macro was done to ensure it was a robust approach to automating this process, but some intervention was required to remove false positives.

Throughout the 2-year monitoring period, researchers periodically sent SMS messages directly to the householders’ smart phones, directing the participants to an online comfort questionnaire (screenshots shown in Fig. 1). More detailed technical information on this online questionnaire platform, aka ‘Comfort Chimp’, can be found in the study done by Parkinson et al. (2013). This very brief questionnaire was designed to be completed in less than one minute, addressing simple questions; (1) identifying whether or not a participant is at home, (2) location inside home, (3) thermal sensation, (4) thermal adaptation strategies in use, and (5) simple classification of clothing type being worn. Table 1 summarises the structure of the questionnaire used for our smartphone surveys. Questionnaires were administered approximately once a week throughout the monitoring period, but during certain weather conditions (e.g. heat waves) it was sent out to the householders more frequently. Participants were allowed to respond to the questionnaire later at a more convenient time, if it arrived at an inconvenient time, as the responses were time-stamped at the point when the questionnaire was completed. The questionnaire was terminated if the participant was not home.

<table>
<thead>
<tr>
<th>Questionnaire item</th>
<th>Measuring scale (coding)</th>
</tr>
</thead>
</table>
| “Are you currently at home?” | - Yes  
- No (questionnaire terminates) |
| Location at home:  “Where are you right now?” | - Living room  
- Bedroom  
- Dining  
- Kitchen  
- Bathroom  
- Laundry  
- Study |
| Thermal sensation:  “How do you feel, right here, right now?” | - Cold (-3)  
- Cool (-2)  
- Slightly cool (-1)  
- Neutral (0)  
- Slightly warm (+1)  
- Warm (+2)  
- Hot (+3) |
| Adaptive strategy:  “In this room here and now, do you have (you may select more than one)?” | - Open windows / doors  
- Ceiling / desk fans operating  
- A/C on (cooling)  
- A/C on (heating)  
- Other heating appliances on  
- None |
| Clothing insulation (clo):  “Which best describes your clothing now?” | - Very light (0.2)  
- Light (0.4)  
- Casual (0.6)  
- Heavy (1.0) |

Throughout the 2-year monitoring period, a total of 4,867 A/C use events and 2,105 online comfort questionnaires were logged. The individual A/C use events and survey responses were matched post hoc with corresponding indoor (measured by iButtons) and outdoor
(obtained from the closest Bureau of Meteorology station) climate observations for subsequent analyses. The prevailing mean outdoor air temperature ($T_{\text{mean(out)}}$) was also calculated (using the weighted 7-day running mean in ASHRAE Standard 55) for the day on which each comfort questionnaire was completed.

3 Results & Discussion

3.1 Characteristics of local climate and participating households

Sydney and Wollongong both belong to temperate climate regions in Australia. In general both cities have characteristics of coastal climate. However the climate of western parts of Sydney becomes more continental as the city spans toward inland due to its greater size. Monthly maximum/minimum outdoor temperatures of Sydney and Wollongong during the 2-year monitoring period, acquired from Australian Bureau of Meteorology, are illustrated in Fig. 2. The mean maximum temperature in Sydney during the monitoring period was 24.2°C, which was 2.7°C higher than that in Wollongong (21.5°C). The mean minimum temperature in Sydney was 12.2°C, which was 2.7°C lower than that reported in Wollongong (14.9°C) for the same period of time. On average, the temperature difference between the coldest and warmest months was relatively greater in Sydney, compared to Wollongong.

![Fig. 2 Outdoor maximum/minimum temperature (monthly average) of Sydney and Wollongong during the monitoring period (data from Australian Bureau of Meteorology)](image)

The participating householders’ characteristics such as gender, the number of people living in the house, the level of education and the gross household income are described in Table 2. The number of female participants was higher (65%) than male participants (35%). The households were mostly comprised of 2 to 4 members (87%).
Table 2 Characteristics of the participating households

<table>
<thead>
<tr>
<th>Description</th>
<th>Category</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
<td>Male</td>
<td>64.6%</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>35.4%</td>
</tr>
<tr>
<td>Household size (persons)</td>
<td>1</td>
<td>4.3%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>40.4%</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>19.1%</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>27.7%</td>
</tr>
<tr>
<td></td>
<td>More than 4</td>
<td>8.6%</td>
</tr>
<tr>
<td>Education level</td>
<td>High school</td>
<td>2.4%</td>
</tr>
<tr>
<td></td>
<td>TAFE (short-cycle tertiary)</td>
<td>9.5%</td>
</tr>
<tr>
<td></td>
<td>University degree</td>
<td>19.0%</td>
</tr>
<tr>
<td></td>
<td>Postgraduate coursework</td>
<td>35.7%</td>
</tr>
<tr>
<td></td>
<td>PhD or research masters</td>
<td>33.3%</td>
</tr>
<tr>
<td>Household income (AUS$)</td>
<td>Up to $10,000</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>$10,001~30,000</td>
<td>2.2%</td>
</tr>
<tr>
<td></td>
<td>$30,001~50,000</td>
<td>6.5%</td>
</tr>
<tr>
<td></td>
<td>$50,001~70,000</td>
<td>13.0%</td>
</tr>
<tr>
<td></td>
<td>$70,001~90,000</td>
<td>10.9%</td>
</tr>
<tr>
<td></td>
<td>$90,001~110,000</td>
<td>13.0%</td>
</tr>
<tr>
<td></td>
<td>More than $110,000</td>
<td>54.3%</td>
</tr>
</tbody>
</table>

3.2 Air-conditioning use patterns

Fig. 3 and Table 3 both summarise air-conditioning usage patterns of the households during the monitoring period. 98% of the A/C cooling events was recorded between late spring and early autumn (October ~ March), with the highest number of cases occurring in January (36%). As reported in Table 3, the room air temperature of 27.9°C was found to be the most common trigger temperature for space cooling among the participating householders. When air conditioning was operating on cooling mode, the average duration of usage was 2.5 hours cooling the room by 2.8°C. Late autumn and winter months (May ~ August) accounted for 89% of the A/C heating events. The A/C was used for space heating for an average of 2 hours, increasing the room temperature by 2.9°C, from 18.2 to 21.2°C.

Fig. 3 Residential A/C events by month (left) and A/C usage duration (right)
### Table 3 Summary of A/C use pattern

<table>
<thead>
<tr>
<th>A/C mode</th>
<th>Description</th>
<th>Household average (S.D.)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cooling</strong></td>
<td>Total A/C (cooling) use per household</td>
<td>155.2 hrs (248.1)</td>
</tr>
<tr>
<td></td>
<td>Average A/C (cooling) use duration per household</td>
<td>2.5 hrs (1.1)</td>
</tr>
<tr>
<td></td>
<td>Cooling trigger temperature (temp when A/C was effectively switched on)</td>
<td>27.9°C (2.0)</td>
</tr>
<tr>
<td></td>
<td>Cooling stop temperature (temp when A/C was effectively switched off)</td>
<td>25.2°C (1.8)</td>
</tr>
<tr>
<td></td>
<td>Cooling ΔT (stop temp – trigger temp)</td>
<td>-2.8K (1.6)</td>
</tr>
<tr>
<td><strong>Heating</strong></td>
<td>Total A/C (heating) use per household</td>
<td>159.8 hrs (208.9)</td>
</tr>
<tr>
<td></td>
<td>Average A/C (heating) use duration per household</td>
<td>2.0 hrs (1.3)</td>
</tr>
<tr>
<td></td>
<td>Heating trigger temperature (temp when A/C was effectively switched on)</td>
<td>18.2 (3.4)</td>
</tr>
<tr>
<td></td>
<td>Heating stop temperature (temp when A/C was effectively switched off)</td>
<td>21.2 (3.6)</td>
</tr>
<tr>
<td></td>
<td>Heating ΔT (stop temp – trigger temp)</td>
<td>+2.9K</td>
</tr>
</tbody>
</table>

### 3.3 Subjective evaluation of the indoor thermal environment

The distribution of room air temperature ($T_{rm}$) recorded at the time of smartphone surveys (therefore the space can be regarded to be occupied) is illustrated in Fig. 4. The majority of survey responses were collected from living room (58%), followed by kitchen (14%), bedroom (11%), study (8%) and dining room (7%). Each bar in Fig. 4 represents the percentage of survey samples falling within each temperature bin. Over 90% of observed room temperature ranged between 18 ~ 29°C. The minimum and maximum temperature observations at survey times were 12.1°C and 36.1°C respectively. In Fig. 4, the distribution of the survey participants’ thermal sensation is also attached. Almost half (47%) of the subjects expressed their thermal sensation as neutral in their homes. Assuming that people voting in the central three categories of the 7-point thermal sensation scale (i.e. **slightly cool, neutral, or slightly warm**) are satisfied with, therefore accepting their thermal environment, overall 83.4% of the participants were satisfied with the thermal conditions in their homes.

![Distribution of room air temperature ($T_{rm}$) logged at the time of questionnaire responses, and thermal sensation votes (TSVs)](image_url)

<table>
<thead>
<tr>
<th>TSV</th>
<th>Cold</th>
<th>Cool</th>
<th>Slightly cool</th>
<th>Neutral</th>
<th>Slightly warm</th>
<th>Warm</th>
<th>Hot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage</td>
<td>0.4%</td>
<td>1.8%</td>
<td>11.6%</td>
<td>46.9%</td>
<td>24.9%</td>
<td>11.7%</td>
<td>2.8%</td>
</tr>
</tbody>
</table>
3.4 Householders’ adaptive behaviours

Clothing insulation is an important variable to investigate occupant behavioural adaptation in residential settings, as individuals would have much more flexibility to adjust their clothing in homes compared to workplaces where a certain dress code is most likely required. The mean value and 95% confidence intervals for the samples’ clo, categorised by indoor room air temperature ($T_{RM}$) binned at 1K intervals, are shown in Fig. 5. This figure describes how residents’ clothing insulation changes depending on indoor temperature variations. A wide range of mean clo-value (0.33~1.0) was observed during the survey period. According to Fig. 5, the subjects’ clothing adaptation was more noticeable when $T_{RM}$ was between about 19 and 26°C. Between 19 and 26°C, the mean clothing insulation decreased by 0.1 clo (from 0.8 to 0.4) for every 1.8°C increase in $T_{RM}$. On the other hand, when $T_{RM}$ was below 19°C or above 26°C, there was no clear tendency of occupants’ clothing adjustments. This implies that thermal adaptation through change in clothing may not be so effective beyond the indoor temperature range of 19~26°C in residential buildings. In other words, thermal adaptability by adjusting clo value in this Australian residential context seems bounded between 0.4 and 0.8 clo.

Fig. 5 Clothing insulation (clo) worn by householders in relation to air temperature ($T_{RM}$) of the room in which they were answering the comfort questionnaire. Error bars represent 95% confidence intervals.

Apart from clothing insulation, our online survey asked householders to identify their means of thermal adaptation at the time when the questionnaire was completed. To understand the participants’ behavioural adaptations in relation to temperature variations, a set of logistic regression analyses were performed with each of the adaptation strategies listed in Table 1 (i.e. Open windows/doors, Ceiling/desk fans on, A/C-cooling on, Heating on) as the dependent variables, and the outdoor air temperature ($T_{A(out)}$) as the independent variable. Thus the logistic regression models predict the probability of people using a particular adaptive strategy to achieve comfort, as a function of outdoor air temperature (Fig. 6).

Based on the results of logistic analyses, the predicted percentage of different adaptive strategies can be estimated as follows:
\[ P(\text{AC-cooling on}) = \frac{100}{1 + \exp^{-(0.24T - 8.20)}} \quad (1) \]
\[ P(\text{Heating on}) = \frac{100}{1 + \exp^{-(0.23T + 3.58)}} \quad (2) \]
\[ P(\text{Fan on}) = \frac{100}{1 + \exp^{-(0.11T - 4.79)}} \quad (3) \]
\[ P(\text{Open windows/doors}) = 100 - \left( \frac{100}{1 + \exp^{(0.33T - 6.58)}} + \frac{100}{1 + \exp^{(-0.17T + 5.13)}} \right) \quad (4) \]

where \( T = \) the outdoor air temperature

According to Fig. 6, \( T_{a(out)} \) of 22 and 28°C were found to be the thresholds that kept the percentage of people relying on mechanical heating and cooling respectively below 20% (note: ‘Heating on’ in Fig. 6 is inclusive of survey votes on both ‘A/C-heating on’ or ‘Other heating appliance on’ given in Table 1). At \( T_{a(out)} \) of about 25°C, ‘A/C-cooling on’ and ‘Heating on’ curves intersected each other, and the frequency of opening windows/doors was peaked. Therefore it seems reasonable to assume that the outdoor temperature of about 25°C is the most favourable temperature condition that can maximise the use of natural ventilation and minimise the householders’ tendency of relying on the mechanical assistance in residential settings. Our findings of the occupant adaptive behaviour schedules as a function of temperature variations given in Fig. 6 can be utilised in energy modelling and simulation software in the Australian residential context. Although more detailed analysis should be followed (e.g. temperature-behaviour relationship by different rooms of the house and by different times throughout the day/night cycle), the result of the analysis can enable household energy efficiency rating tools such as AccuRate to perform more realistic, and therefore more precise energy assessments.

Fig. 6 The predicted percentage of adaptive strategies in use as a function of outdoor air temperature

\[ T_{a(out)} \]
3.5 Thermal sensation, acceptability, and the predicted percentage of dissatisfied

The relationship between thermal sensation votes (TSVs) and concurrent indoor temperature was investigated by fitting a linear regression between the two variables (Fig. 7). In comfort studies, the gradient of the regression model is typically interpreted as being inversely related to occupants’ thermal adaptability. In other words, the steeper the regression line is, the more sensitive (or the less tolerant) the occupants are to temperature variations. In our analysis, the temperature difference ($T_{\text{diff}}$) between room air temperature ($T_{\text{rm}}$) and neutral temperature ($T_n$, calculated according to the ASHRAE 55’s adaptive model: i.e. $T_n=0.31T_{\text{pma(out)}}+17.8$) was computed for each of the survey samples (i.e. $T_{\text{diff}} = T_{\text{rm}} - T_n$). Positive values of $T_{\text{diff}}$ signify that room temperature is above the neutral temperature estimated by the ASHRAE 55’s adaptive model, while negative values indicate that room is cooler than the neutrality. Then, TSVs were regressed on this relative temperature scale (binned into 0.5K intervals of $T_{\text{diff}}$), so the regression model was weighted by the number of TSVs falling in each of the $T_{\text{diff}}$ bin (Fig. 7).

![Fig. 7 Thermal sensation votes (TSVs) regressed on the relative temperature scale (i.e. room air temperature minus neutral temperature predicted by ASHRAE 55 adaptive model, $T_{\text{diff}} = T_{\text{rm}} - T_n$). Regression line is weighted by the number of TSVs falling in each of the half-degree temperature bins.](image)

The logic behind using temperature offset from neutrality (i.e. $T_{\text{diff}}$) as the independent variable of the regression model rather than simply using room temperature, rests with the fundamental concept of adaptive comfort, which suggests that perception of thermal comfort can be influenced by contextual factors such as outdoor climate, seasons, past and current thermal experience (Brager and de Dear, 1998). For example, according to the adaptive theory, the same indoor temperature can be felt differently between those who have different thermal history. In our study, TSVs were collected from 42 different locations for the duration of 2 years encompassing two full cycles of seasonal changes. As a result, there was no basis to assume that each of the collected TSVs carried the equivalent thermal experiences prior to the survey. $T_{\text{diff}}$ in this analysis was used in order to adjust the differences in individuals’ thermal history across two years of the monitoring period, which might have influenced their TSVs.

The final regression model ($R^2=0.91$, significance level of coefficient and constant $p<0.001$) derived from the entire sample is:

$$TSV = 0.16 \times T_{\text{diff}} + 0.39 \quad (5)$$
According to the regression model, 6.3K of temperature change accounts for one unit change of thermal sensation on the 7-point scale (one over the regression coefficient of 0.16 in Equation 5). Interpreting the gradient of the regression equation as the group’s thermal sensitivity, occupants of residential buildings were 70% more tolerant to indoor temperature variations, compared to occupants of naturally ventilated office buildings (comparing with the mean regression model gradient of 0.27 reported by de Dear and Brager (1998), whose study has been adopted as the ASHRAE 55’s adaptive comfort standard). With more than 6K required to increase/decrease one thermal sensation unit, this group of householders was successfully adapting to the changes in indoor temperature conditions.

The estimated neutral temperature, by solving the equation for TSV of zero, was -2.4K. This means that the neutrality for this sample group in residential settings was 2.4K cooler than that predicted by the ASHRAE 55’s adaptive model. This finding is in lines with studies reporting house residents’ cooler-than-expected neutral (or preferred) temperatures (Oseland 1995; Pimbert and Fishman 1981).

In this study thermal acceptability was defined as the percentage of TSVs falling within the middle three categories of the 7-point (continuous) thermal sensation scale (i.e. -1.5<TSV<+1.5). The proportion of ‘acceptable’ votes was calculated for each half-degree bin of T\(_{\text{diff}}\) and is illustrated in Fig. 8. Then a fit-curve was produced, weighted by the number of samples falling within each of the bins. The fit-curve was skewed toward the left side of the T\(_{\text{diff}}\) scale, reporting higher percentage of acceptability on ‘cooler-than-neutral’ temperatures. While the householders’ thermal acceptability generally maintained higher than 80% in cooler-than-neutral conditions, it started dropping below 80% at which indoor temperature was 2K warmer than the neutrality. Then again significant decrease in acceptability was observed as indoor temperature exceeded more than about 3 degrees higher than the neutral temperature. The present analysis indicates that residents required cooler temperature conditions than predicted by the standard in order to meet the 80%
acceptability target. Additional work seems essential to explore the potential drivers that make householders more tolerant in cooler-than-neutral conditions. However, householder’s behavioural/psychological adjustments to cooler temperature conditions that couldn’t be captured in our study might have played a role: such as using blankets, moving closer to warm radiant source (e.g. sunlight through window), exercising, cooking, and concerns on energy bills.

Further elaborating the analytical approach just used to calculate thermal acceptability in Fig. 8, a predictive model that is capable of estimating the percentage of people dissatisfied due to warm- or cool discomfort can be derived. The logic behind this analysis is directly comparable to that used by Fanger (1972) when he derived the PPD (Predicted Percentage of Dissatisfied) index from the PMV (Predicted Mean Vote) estimation. ‘Warm discomfort’ votes (TSV>+1.5, i.e. warm or hot) and ‘cool discomfort’ votes (TSV<-1.5, i.e. cool or cold) were binned into 0.5K intervals of T_diff and became the basis of probit regression models predicting what percentage of people is expected to be cool- or warm dissatisfied (probit models’ significance level for coefficient and intercept: p<0.001). Then they were added into one curve representing the total percentage of dissatisfied as a function of temperature offset from the neutrality (Fig. 9). The predictive curve has a minimum value of 9% (PPD) when indoor temperature was 3K cooler than expected by the ASHRAE 55 adaptive model. This is in line with the result of an earlier filed study conducted in hot-humid climate (Hwang et al. 2009) in which the minimum value of PPD was estimated to be 9% and the PPD curve shifted towards the cool side of the scale. An increase of the minimum PPD to 9% from 5% suggested by Fanger (1972) is not surprising, as the PPD from climate chamber experiments has been found to be substantially underestimating the dissatisfaction rate observed in actual buildings (Arens et al., 2010). Considering the fact that ASHRAE Standard 55 presumes another 10% dissatisfied resulting from local discomfort in addition to the PPD value, minimum 9% of total dissatisfied rate seems more realistic as local discomfort issues are already factored into the current adaptive approach.

Fig. 9 Predicted proportion of thermally dissatisfied individuals in their homes, as a function of temperature offset from the ASHRAE 55’s adaptive model neutrality. There are no numbers on the Y axis.
Now the point of intersections between the predictive curve and 20% dissatisfied can be used to define the boundaries of 80% comfort zone. According to Fig 9, the range of temperatures at which more than 80% of the subject felt comfortable (i.e. PPD < 20%) was estimated to be 9K. The span of acceptable indoor temperatures for the current resident samples came to 9K, which is 2K wider than the width of ASHRAE’s 80% acceptability (ASHRAE, 2013). Therefore our hypothesis that occupants in houses will have a wider range of comfort zone due to greater adaptive opportunities was supported by the empirical findings.

Our analyses so far have shown that occupants’ reaction towards the thermal environments in their homes appeared to be considerably different to what suggested by previous adaptive comfort studies that were based on office building contexts. As seen in Fig. 7 and Fig. 8, the householders’ group mean neutral temperature and optimal temperature drifted 2~3K towards cooler side of the relative temperature scale, compared to that estimated by the ASHRAE 55’s adaptive model. Interpreting regression slope in Fig. 7 as an index of thermal adaptability, people seemed to be more adaptable in their homes than in workplaces. Residents’ greater adaptability was also confirmed in Fig. 9 in which the comfort range for 80% acceptability was estimated to be 2K wider than the ASHRAE 55 adaptive standard. Given the noticeably different empirical findings between home and workplace settings, it seems to be meaningful with no doubt to revisit the adaptive comfort model in the context of residential settings, in order to better understand occupants comfort and adaptive behaviours in their homes.

3.6 Adaptive model for residential comfort

To investigate the fundamental concept of adaptive comfort that the indoor neutral temperature depends on the prevailing mean outdoor temperature (Humphreys, 1978; Nicol and Humphreys, 2002), the following analytical steps were taken:

1. The entire survey samples were divided according to the month and the city, obtaining 24 sub-groups (i.e. 12 months × 2 cities).
2. A weighted linear regression model was fitted separately to each of the 24 sample groups, to quantify the relationship between the group mean thermal sensation and indoor room temperature (TSV = b × T_{rm} + c). Excluding regression models failed to achieve 95% significance, a total of 14 regression models retained for further analysis; mean model gradient \( b = 0.17 \), mean model constant \( c = -3.67 \), mean sample size \( n = 76 \), and mean \( R^2 = 0.51 \).
3. The neutrality temperature was calculated from each of the 14 regression equations, then matched with the concurrent prevailing mean outdoor temperature (\( T_{pma(out)} \)).

The association between our residential sample’s monthly neutral temperature (\( T_{n(resi)} \)) and prevailing outdoor temperature (\( T_{pma(out)} \)) is graphed in Fig. 10. Indoor neutrality tended to increase as outdoor temperature became warmer, validating the hypothesis of adaptive comfort model in the residential context. The regression equation defining the relationship between \( T_{n(resi)} \) and \( T_{pma(out)} \) achieved statistical significance (\( p<0.05 \)) and is as follows:

\[
T_{n(resi)} (^{\circ}C) = 0.26 \times T_{pma(out)} + 16.75 \quad (R^2 = 0.37)
\]
The next step was to define acceptable temperature limits from Equation 6. In the ASHRAE 55’s adaptive comfort standard, a regression equation fitted between group mean TSV and indoor temperature was used to define the acceptability boundaries. That is, 80% acceptability limits in the ASHRAE 55 adaptive model was determined by solving the regression equation for TSV of ±0.85 (de Dear and Brager, 1998). The logic behind this definition was directly derived from Fanger’s PMV-PPD relationship in which PPD reaches 20% when the group mean thermal sensation (PMV) equals ±0.85 (Fanger, 1972). However, in the present study the predictive curve showing the relationship between the proportion of thermal dissatisfaction and temperature variations (Fig. 9) has already produced 80% acceptability zone without having to borrow Fanger’s PMV-PPD curve. Plus, there is no empirical basis to assume that the PMV-PPD relationship derived from climate chamber experiments is directly applicable to real world setting, in particular residential buildings where people are given with nearly all kinds of adaptive opportunities. As already shown in Fig. 10, the comfort range for 80% thermal acceptability was 9K. The 9K for 80% acceptability band, centred on the neutral temperature in Equation 6, determined upper and lower 80% acceptability limit as follows:

Upper 80% acceptability limit (°C) = 0.26 \times T_{pma(out)} + 21.25 \quad (7)

Lower 80% acceptability limit (°C) = 0.26 \times T_{pma(out)} + 12.25 \quad (8)

The 80% acceptability range derived from our analysis on residential samples, compared against that of the ASHRAE 55 adaptive standard, is depicted in Fig. 11. It should be noted that the comfort zone of residents proposed in this study is only defined within the prevailing mean outdoor temperature of approximately 8 ~ 27 °C, due to the lack of data samples with \( T_{pma(out)} \) values falling beyond this range. The width of 80% acceptable temperature range in the present study was about 30% wider (2K) than that prescribed in the ASHRAE 55’s adaptive comfort standard. Despite of the wider comfort range, householder’s comfort zone shifted down toward lower indoor temperatures due to their approximately 2K-cooler neutrality than that of the ASHRAE 55 adaptive model. Fig. 11 suggests that occupants of houses are more tolerant of, or more adaptable to cooler temperature variations than occupants of office buildings.
Fig. 11 Comparison of the 80% acceptable temperature ranges between the ASHRAE 55’s adaptive comfort model and the proposed residential adaptive model in the present study

To test and validate the residential comfort zone just proposed in Fig. 11, the entire A/C events data samples \((n=4,867)\) recorded during our monitoring period was utilised. Indoor room temperature readings when A/C was effectively switched off were assumed as the residents’ comfort temperatures. These AC ‘stop’ temperatures may not be the perfect index of comfort/preferred temperature inside the room in which AC was used, as there could be cases that A/C was switched off simply because the room in question was not occupied, regardless of occupant comfort. Nevertheless, it seemed rational, for most of the cases, to regard the AC ‘stop’ temperature as a good approximation of the residents’ comfort temperature. Then, supposedly, more than 80% of those temperature readings should fall within the 80% acceptability range of the adaptive comfort model. Fig. 12 illustrates indoor temperatures when A/C was switched off as a function of prevailing mean outdoor temperature, plotted against the 80% acceptable zone prescribed by ASHRAE 55’s adaptive comfort standard and the current study. The percentage of data points falling within or beyond the acceptable temperature ranges is also summarised in Fig 12. Out of total 4,867 A/C ‘stop’ temperature observations, 70.4% fell within the ASHRAE 55’s adaptive 80% acceptability range, indicating about 10% of discrepancy between the predicted and the observed (for the dots falling outside of the vertical boundaries of the 80% acceptability zone, i.e. \(T_{pma(out)}<10\)°C, it was assumed that the upper- and lower- boundaries will continue on the same gradient). A considerable number (24.5%) of the AC ‘stop’ temperature observations fell below the lower 80% limit of the ASHRAE 55 adaptive model, implying that the model is overestimating the comfort temperature of occupants in homes and underestimating home occupants’ adaptability to lower temperature conditions. On the other hand, comparing the same A/C events data against the residential adaptive model, 80.4% of data samples fell within the 80% acceptability limits. And the percentage of samples falling over the upper 80% limit and under the lower 80% limit was almost identical.
at 10.1% and 9.5% respectively. Therefore it seems reasonable to assume that the proposed 80% acceptable temperature range in this study provides usable predictability of home residents’ comfort temperatures.

![Diagram](Image)

<table>
<thead>
<tr>
<th></th>
<th>ASHRAE 55 adaptive model</th>
<th>Proposed residential adaptive model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Within range</td>
<td>70.4%</td>
<td>80.4%</td>
</tr>
<tr>
<td>Above 80%</td>
<td>5.1%</td>
<td>10.1%</td>
</tr>
<tr>
<td>Below 80%</td>
<td>24.5%</td>
<td>9.5%</td>
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Fig. 12 Indoor A/C (cooling or heating) ‘stop’ temperatures (n=4,840) plotted against the 80% acceptability range defined by the ASHRAE 55 adaptive model and the present study (top). Percentage breakdown of the data points shown in the table (bottom).

Although Fig. 12 suggests that the proposed residential adaptive model is valid in predicting comfort of home occupants, more research work is necessary to strengthen the predictability and the applicability of the model. While the ASHRAE 55’s adaptive comfort standard was based on the data from different locations covering a broad spectrum of climate zones (de Dear, 1998), the sample used in the current study came exclusively from temperate climate regions. As a result, the comfort zone when a prevailing mean outdoor temperature falls beyond the range of 8 ~ 27 °C couldn’t be defined (Fig. 11). Data collected from more extreme climate regions is required to strengthen the predictability of the proposed model and to widen its boundaries.

4 Conclusions
This paper presented results from an extensive field study on thermal comfort and adaptive behaviours carried out in Australian homes. The participating householders’ thermal sensations and adaptive strategies collected through a smartphone comfort questionnaire were compared with the corresponding indoor and outdoor climatic data. The statistical analysis performed on the entire samples provided sufficient empirical evidences to enquire
'classic' research questions in thermal comfort research including neutrality, sensitivity, acceptability, adaptive behaviours and comfort zone. An outdoor temperature of 25°C was found to be the most favourable condition in terms of maximising the use of operable windows/doors and minimising occupant reliance on mechanical air-conditioning (Fig. 6). Both linear and probit models fitted between thermal sensation votes and temperature variations (Fig. 7 and Fig. 9) estimated that the neutrality of home occupants fell about 2~3K cooler than the ASHRAE 55 adaptive comfort standard’s prediction. Occupants in homes were more tolerant particularly in cooler temperature conditions than expected by the comfort standards. Despite the cooler-than-expected neutrality, occupants of residential buildings showed a greater degree of thermal adaptability compared to that expected for office occupants, taking 6.3K of temperature change to shift one unit on the 7-point thermal sensation scale (Equation 5). According to our predictive model (Fig. 9), the span of indoor temperatures for 80% acceptability came to 9K, which is 2K wider than the width of the ASHRAE 55 adaptive model’s 80% acceptability. Based on our findings, an adaptive model for residential building was proposed to estimate comfort temperatures in relation to outdoor temperature variations (Equation 6 and Fig. 11).

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