Air Conditioning Usage and Environmental Control Behaviour in Residential Contexts

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Abstract

While the role of occupants is deemed crucial in building energy use, little is known how they interact with the built environment to maintain comfort, especially in residential contexts. The study aims to better characterise occupant air-conditioning (AC) use decisions and comfort behaviours within households. Combining instrumental measurements and smartphone surveys, we monitored AC usage patterns, indoor and outdoor climatic factors, and environmental adjustment behaviours in Australian homes. Our field observations reveal the patterns of residential AC operation such as AC usage duration and trigger temperatures for space cooling / heating. The analysis on self-reported behaviour data derives statistical models to enable predicting of occurrence of environmental control behaviours including operation of AC, fans and windows, in relation to the external climate factor.

Introduction

Despite air-conditioning (AC) having become one of the fastest growing energy end-uses in the Australian residential sector (DEWHA, 2008), there have been no rigorous research into occupant AC usage patterns and adaptive comfort behaviours within the residential context. Thermal comfort studies focused on residential settings are rare, compared to office environment comfort studies. This is probably due to logistical difficulties, as peoples' homes are geographically dispersed, together with potential concerns regarding long-term installation of equipment and resident privacy, in contrast to office building contexts where researchers can quickly collect large amounts of data from a concentrated sample of occupants.

Previous studies identify occupant behaviour as a key source of uncertainties in building energy use (e.g. D'Oca et al., 2014; Gunay et al., 2013; Yan et al., 2015). While understanding the interaction between a building and its users is regarded important for improving the performance of building energy simulations, studies point out that standard occupant behaviour profiles programmed into simulation tools are too simplistic to fully represent real-life situations (e.g. Andersen et al., 2009; Hong et al., 2015; Langevin et al., 2015). Nicol and Humphreys (2004) suggested a stochastic approach to analysis of the occupant behaviour, which has been popularly utilised in subsequent studies as a solution to address this issue of simplistic behavioural schedules (e.g. Haldi and Robinson, 2008; Rijal et al., 2007; Schakib-Ekbatan et al., 2015; Schweiker et al., 2012; Schweiker and Shukuya, 2008, 2009; Schweiker and Wagner, 2015; Yun and Steemers, 2008).

Compared to office workers, occupants in their homes play a more active role in maintaining comfort by exerting direct control over the indoor climate (e.g. adjusting temperature set-point, operating AC or heater, and opening windows or doors) and by engaging themselves in more diverse activities (e.g. adjusting clothing insulation levels, taking a shower or a bath, and drinking hot or cold beverages). Therefore the impact of environmental interventions by occupants on building energy consumption is expected to be greatest in residential settings. Notwithstanding the complexity of human behaviours and the mechanism behind thermal adaptation, this paper aims to better understand interactions between householders' environmental control behaviours and indoor/outdoor climatic conditions. The results of a longitudinal field study conducted in a sample of Australian residences are reported, with a primary focus on householders' AC usage decisions and comfort-related behaviours.

Methods

Instrumental measurements

Instrumental monitoring was carried out for a period of two years in 42 Australian households. The participating households were located across two neighbouring cities (Sydney and Wollongong), both falling within the same climate zone characterised by humid sub-tropical summers and mild, temperate winters. Only those homes equipped with an air-conditioning system were recruited for this study. Characteristics of the participating homes are summarised in Table 1.

Very small, autonomous data-logging devices (*iButtons*) were installed in various locations within the occupied zones of the participants' homes, recording indoor air temperature 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 AC units were being used.

Sudden changes in the time-series of AC supply air temperature defined AC switch-on or switch-off events, and these were compared to the simultaneous temperature recorded in the occupied zone of the room in question to determine the AC mode (heating/cooling) in operation. First, if the difference between two successive supply air temperature measurements was greater than 3.5°C (per 15 minutes) then the AC was considered to be switched on or off within that 15-minute period. The temperature in the occupied zone when the AC was operational and two subsequent measurements (three in total) were then analysed; the three sequential measurements safeguarded against temperature cycling being misclassified as AC switch-on or switch-off events. 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. A total of 4,867 AC use events were logged throughout the 2-year monitoring period. In addition, outdoor weather observations were obtained from the Bureau of Meteorology stations that were geographically closest to each participating household.

Table 1: Characteristics of the participating households

Description	Category	Percentage
Household size (persons)	1	4.3%
	2	40.4%
	3	19.1%
	4	27.7%
	More than 4	8.6%
House/unit details	One storey	38.1%
	Split level	14.3%
	Two storey	28.6%
	Other	14.3%
	Unknown	4.8%
Main materials – walls	Double brick	33.3%
	Brick veneer	38.1%
	Timber	7.1%
	Lightweight cladding	7.1%
	Other	7.1%
	Unknown	7.1%
Air conditioning system type	Ducted	14.3%
	Wall/window units	9.5%
	Fixed split units	66.7%
	Portable units	2.4%
	Unknown	7.1%

Smartphone surveys

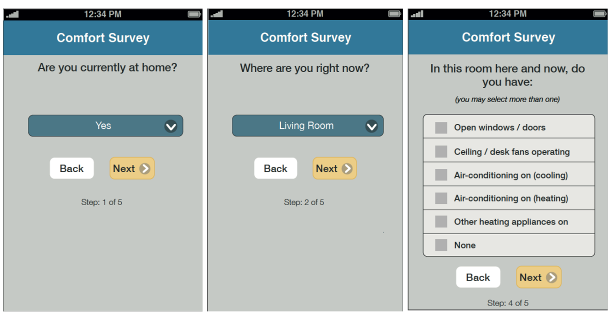

Figure 1: Smartphone questionnaire

Throughout the 2-year monitoring period, we periodically sent SMS messages directly to the householders' smartphones, directing recipients to a short online comfort questionnaire. This very brief questionnaire asked the participants to report (1) whether or not a participant was at home, (2) in which room of the home they were located, and (3) thermal adaptive behaviours in use at the time of survey. Figure 1 shows screenshots of the smartphone questionnaire. Each smartphone survey response (n=1,525) recorded throughout the monitoring period was matched *post hoc* with the corresponding temperature observations in the same room for subsequent statistical analyses.

Results & Discussion

AC usage patterns

Figure 2 illustrates the distribution of AC use events recorded during the monitoring period (n=4,867). Each bar represents the number of either 'cooling' or 'heating' events falling within each month. 98% of the AC operation events for space cooling were registered between October and March, which spans the Austral late spring through early autumn. According to Figure 2, the highest number of AC-cooling events was recorded in January (36%). In general heating season spanned late autumn through winter (May ~ August), accounting for 89% of the total AC-heating events in the database.

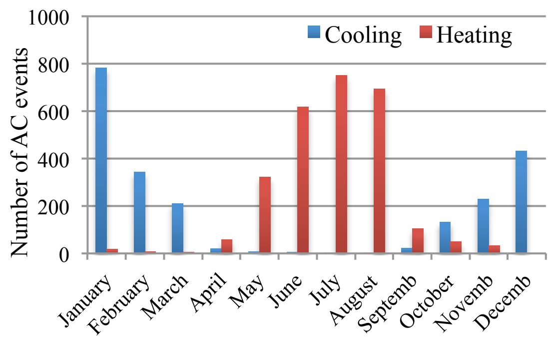

Figure 2: Residential AC use events by month

The boxplots in Figure 3 show the distribution of coincident room temperatures when an AC unit was switched on or off. The *trigger temperature* is defined as the coincident room temperature when the AC was switched on – i.e. room temperature immediately prior the AC unit's *iButton* detecting a status change to "on". The term *stop temperature* denotes the room temperature when the AC system was switched off – i.e. the room temperature immediately prior the AC unit's *iButton* detecting a status change to "off". According to Figure 3, the lower and upper quartile for the *cooling trigger temperature* was 25.1 and 28.1°C. The *cooling stop temperature* was about 2-3 degrees lower than the *trigger temperature* (the lower and upper quartile: 22.6 and 25.7°C). 50% of the AC-heating periods were initiated at room temperature between 15.1 and 19.1°C. At the time the AC in heating mode was switched off, the room temperature had increased about 2-3 degrees warmer than when it was turned on (the lower and upper quartile: 16.6 and 22.1°C).

One of the limitations of the current study was the lack of occupant presence data in each room of the monitored building. This means that there could be cases that AC switch on/off decisions were made irrespective of occupant 'comfort' in a room – e.g. 'AC off' because the room in question was no longer occupied or 'AC on' simply because the room was just occupied. It explains outliers registered at very high/low temperatures in Figure 3.

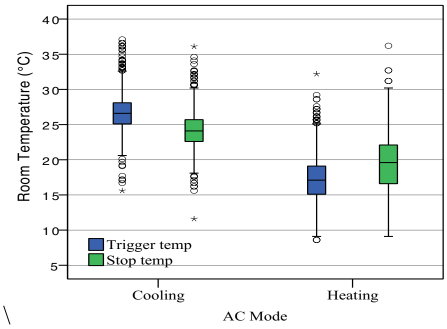

Figure 3: Boxplots for trigger/stop temperature by AC mode (the top and bottom of the box represent the upper and lower quartile)

Table 2 summarises patterns of AC usage in our sample of 42 Australian households. A room temperature of 27.9°C was found to be the most common *trigger temperature* for space cooling among the participating homes. On average, the householders operated air-conditioning in cooling mode for 2.5 hours, cooling the room by 2.8°C (ΔT). The AC system in space heating mode was used for an average of 2 hours, heating up the room from 18.2 to 21.2°C (ΔT=2.9°C).

Table 2: Summary of AC use patterns

AC mode	Description	Household average (S.D.)
Cooling	Total A/C (cooling) use per household	155.2 hrs (248.1)
	Average A/C (cooling) use duration per household	2.5 hrs (1.1)
	Cooling trigger temperature	27.9°C (2.0)
	Cooling stop temperature	25.2°C (1.8)
	Cooling ΔT (stop temp – trigger temp)	-2.8K (1.6)
Heating	Total A/C (heating) use per household	159.8 hrs (208.9)
	Average A/C (heating) use duration per household	2.0 hrs (1.3)
	Heating trigger temperature	18.2 (3.4)
	Heating stop temperature	21.2 (3.6)
	Heating ΔT (stop temp – trigger temp)	+2.9K

The adaptive comfort model used in the most recent version of ASHRAE Standard 55 (ASHRAE, 2013) quantifies the dependence of acceptable indoor comfort temperatures on prevailing mean outdoor air temperature, $T_{pma(out)}$. $T_{pma(out)}$ is derived as an arithmetic average of the mean daily outdoor temperatures over a certain period of days presumed to be the outdoor climatic context to which occupants have become adapted (ASHRAE, 2013). According to the adaptive model (de Dear and Brager, 1998; Humphreys, 1978), the indoor comfort zone tracks prevailing outdoor weather – shifting up in warm weather and down in cool weather. The adaptive comfort hypothesis implies that householders' AC use decisions can be affected by the climatic conditions prevailing outdoors.

To examine the dependence of residential AC usage on the outdoor climatic environment, we have calculated a $T_{pma(out)}$ that corresponds to each of the AC events logged in our database. We have used the 7-day running mean exponential decay function in our calculation of $T_{pma(out)}$ (Morgan and de Dear, 2003), capturing the external climatic dynamics that have influenced human adaptation during the preceding 7 days. The mean value and 95% confidence intervals for the *cooling trigger / stop temperatures* during the cooling season (October ~ March), categorised by $T_{pma(out)}$ binned at 1°C intervals, are illustrated in Figure 4. Therefore this figure describes how householders' AC cooling switch on/off decisions relate to the outdoor meteorological driver.

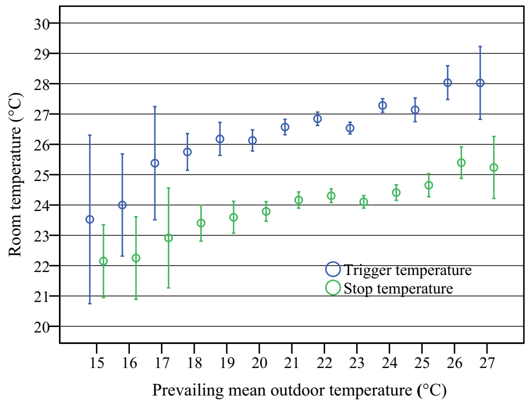

Figure 4: Trigger/stop temperatures for AC cooling, in relation to prevailing mean outdoor air temperature (°C) (error bars represent 95% confidence intervals)

In general, an upward trend is discernible in Figure 4 – householders switched AC-cooling on/off at higher indoor temperatures when the outdoor weather became warmer. The indoor temperature that triggered AC-cooling switch-on decisions drifted up from 23.5 to 28°C as the prevailing outdoor temperature rose from 15 to 27°C. Likewise, the indoor temperature at which householders switched the AC off, also shifted up from 22.2 to 25.2°C across the same range of prevailing outdoor temperatures. These findings indicate that householders' AC usage is related to the external climatic context – decisions about when to turn on/off AC depend on the weather dynamics recently experienced. The fundamental concept of the adaptive comfort model that defines the dependence of indoor comfort zone on outdoor weather is supported by these new behavioural data.

Adaptive comfort behaviours

Throughout this 2-year longitudinal project, the participating householders periodically (approx. once per week) reported their environmental comfort behaviours at the time when they were responding to the smartphone questionnaire (n=1,525). Among those comfort behaviour options (adaptive opportunities) given in the questionnaire (see Figure 1), '*open windows/doors*' was identified as the most frequently reported (39.5%), followed by '*heating appliances on*' (23.1%, the sum of '*AC heating*' and '*other heating appliances on*'), '*AC cooling on*' (13.6%), and '*ceiling / desk fans operating*' (12.6%).

Statistical analysis was performed on our survey dataset in order to derive numerical models to describe the householders' adaptive comfort behavioural patterns in relation to temperature variations. We used the outdoor air temperature registered at the nearest weather station as the independent variable, rather than the indoor air temperature logged through *iButtons* because indoor temperature under these circumstances can simultaneously be both a *cause* and an *effect* of the environmental adjustment behaviour. For example, turning on AC or heating appliances would have directly affected the indoor temperature, meaning that the indoor temperature is no longer independent of the outcome variable.

Table 3 summarises the results of logistic regression models fitted to '*AC cooling on*', '*heating on*' and '*fan on*' responses. All models reached statistically significant regression coefficients (*b*) and constants (*c*), together with usable predictability (R^2). As majority of the previous studies cited in this paper omit to report R^2 values for their stochastic behaviour models, hence it becomes difficult to directly compare our results against others in regard of the model predictability. Nevertheless, R^2 values of the current logistic models are generally higher than that of previously reported behavioural models (e.g. Haldi and Robinson, 2008; Schweiker and Shukuya, 2009).

Table 3: Logistic regression models for environmental adjustment behaviours

Dependent variable	***b* [95% CIs]**	***c***	**R^2 (Nagel kerke)**	**Model Chi-square (χ^2)**
AC (cooling) on	0.24^{**} [0.27,0.21]	-8.20^{**}	0.40	383.15^{**}
Heating appliances on	-0.23^{**} [-0.26,-0.21]	3.58^{**}	0.46	568.14^{**}
Fans on	0.11^{**} [0.09,0.14]	-4.79^{**}	0.15	98.97^{**}

Note: independent variable = outdoor air temperature; *b* = regression coefficient; *c* = constant; $^{**}p<0.001$

Based on the results of the logistic analysis reported in Table 3, the probability of different control behaviours in use, as a function of the outdoor air temperature can be defined as follows:

$$p\ (AC\text{-}cooling\ on) = \frac{1}{1+exp^{-(0.24T-8.20)}} \qquad (1)$$

$$p\ (heating\ on) = \frac{1}{1+exp^{-(-0.23T+3.58)}} \qquad (2)$$

$$p\ (fan\ on) = \frac{1}{1+exp^{-(0.11T-4.79)}} \qquad (3)$$

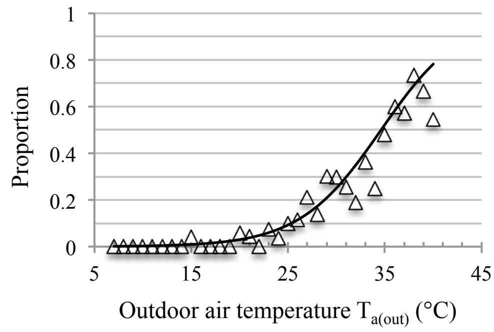

Figure 5: Proportion of householders using AC on cooling mode, in relation to the outdoor air temperature (°C)

The logistic curves defined in Equation 1~3 are illustrated in Figure 5~7, together with binned survey responses (1 degree intervals). Figure 5 indicates that the proportion of householders switching on the AC-cooling increases as the outdoor temperature ($T_{a(out)}$) rises. The growth of AC usage was very modest until *circa* $T_{a(out)}$ 25°C. Then there was a sharp increase of AC (cooling) usage as $T_{a(out)}$ exceeded 27°C. According to the logistic model, half of householders operate AC when $T_{a(out)}$ reaches 35°C.

Figure 6 shows the pattern of heating appliance usage across the $T_{a(out)}$ range. The likelihood of householders operating heating appliances significantly increased as $T_{a(out)}$ dropped below 25°C. According to Figure 6, more than half of the householders are expected to use their heating appliances at $T_{a(out)}$ of below 15°C.

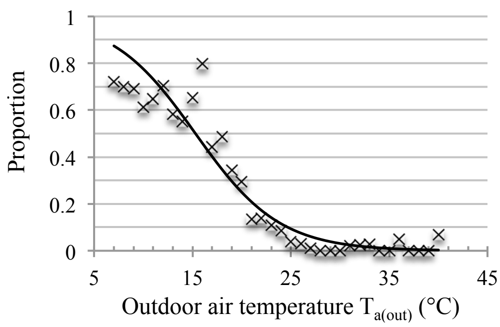

Figure 6: Proportion of householders using heating appliances, in relation to the outdoor air temperature (°C)

The proportion of fan usage was consistently lower than 40% in our sample of householders, across the entire range of $T_{a(out)}$ observations (Figure 7). The slope of the logistic curve was much more gradual than 'AC cooling on ' or 'heating appliances on' curves, indicating that fan usage is less weather sensitive. The results imply that these Sydney/Wollongong householders are less likely to use fans than other environmental control devices at their disposal, including AC and heating appliances.

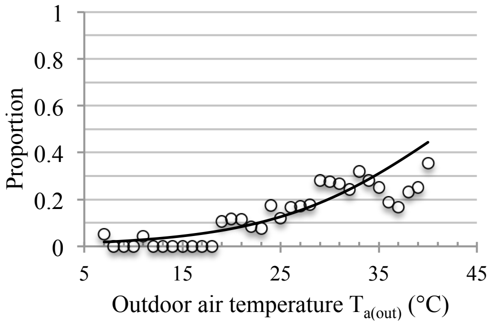

Figure 7: Proportion of householders using ceiling/desk fans, in relation to the outdoor air temperature (°C)

While the behavioural patterns shown in Figure 5~7 were well described by logistic functions based on a linear regression (sigmoid curve), the patterns of window operation behaviour observed in our study was somewhat different, following a 'bell curve'. Figure 8 illustrates the actual proportion of 'open windows/door' responses for each of the 1°C bins (data points). This figure clearly shows both positive and negative dependence of the outcome variable on outdoor air temperature variations. Thus a logistic function, based on a second-order polynomial regression, was fitted to the '*open windows/doors*' data (R^2=0.24). The resulting numerical model, estimating the probability of householders opening windows or doors, is:

$$p\ (window/door) = \frac{1}{1+\exp^{-(-0.02T^2+0.99T-12.07)}} \quad (4)$$

According to Figure 8, more than half of Sydney/Wollongong householders with AC in their homes are expected to rely on natural ventilation through open windows and/or doors when $T_{a(out)}$ falls between 20 and 32°C. The maximum proportion (68%) of opening windows/doors occurs at *circa* $T_{a(out)}$ 25°C.

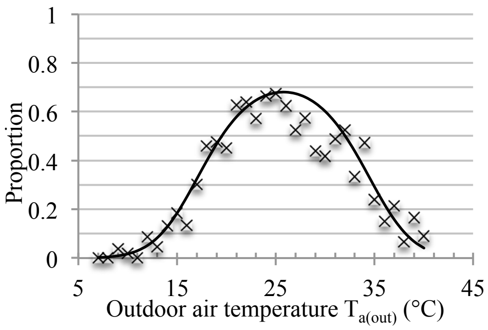

Figure 8: Proportion of householders opening windows/doors, in relation to the outdoor air temperature (°C)

The current analysis is based on a sample of 42 Australian households in the Sydney and Wollongong region. Indeed a larger sample is necessary to support deeper analyses to further investigate temperature-behaviour relationships for different room types and diurnal occupancy pattern. It also seems noteworthy that the entire field data was collected from the same climate zone - humid sub-tropical summers and mild, temperate winters, and broadly the same socio-ecomomic and cultural context. Therefore a suggestion for future research is to collect field data from various climate regions and socio-economic and cultural contexts in order to investigate how occupant behavioural pattern changes across different climate contexts.

Conclusion

We conducted a 2-year longitudinal field study focusing on householders' environmental adjustment behaviours. Smartphone surveys and autonomous *in situ* data logging devices were first utilised in the Australian residential context and shown to be very effective at long-term data collection from geographically dispersed locations. The instrumental monitoring revealed that the most common trigger temperature for air-conditioning was 28°C for cooling and 18°C for heating. Typically, householders operated AC to heat up or cool down the space by 3 degrees. An interesting finding from our AC events data was that householders adjusted their decisions on when to switch on/off AC according to prevailing external climatic conditions. Temperature thresholds of householders' space cooling decisions tended to become more relaxed (warmer) as the prevailing mean outdoor temperature rose, implying that householders adapted to warmer meteorological environments which in turn weakened their reliance on air conditioning to achieve acceptable indoor climates. Our analysis on the self-reported behavioural data indicated that operation of windows/doors was the most typically observed behaviour for environmental adjustment in our sample of householders. We also presented stochastic models quantifying the occurrences of a particular environmental adjustment as a function of outdoor temperature, to better characterise occupant adaptive behaviours in residential settings.

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