The effect of air conditioners on occupants' thermal adaptive behaviours and wellbeing: advances and challenges

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Abstract. To study the impact of air conditioners (AC) on occupants' behaviours and comfort, two comparison surveys were conducted during hot summer weather before and after air conditioners were installed in student dormitories at Chongqing University in 2008 and 2016, respectively. The results showed that after the ACs were installed, occupants' environmental satisfaction vote was notably higher irrespective of whether the equipment was used. The proportion of ACs used (PAU) in 2016 and the proportion of fans used (PFU) in 2008 were logistically fit with the outside temperatures, and these data displayed very similar trends. However, less variety in adaptive behaviours was evident after the ACs were installed. When ACs were used, lower proportions of windows were opened (13%) and higher proportions of occupants felt stuffy (54%), experienced draughts (38%), and reported sick building syndrome (SBS). This study provides scientific insight into the advances and problems caused by the popularization of ACs.

1 Introduction

Before the air conditioner (AC) was invented, human beings worldwide suffered from changing weather conditions and developed adaptive skills involving behavioural, physiological, and psychological traits [1]. With the popularization of the AC, indoor thermal conditions and quality of life dramatically improved, especially on hot summer days. However, several problems such as sick building syndrome (SBS) [2], the energy crisis [3], and global warming have been drawing increasing attention from the public and researchers [4, 5], and thus, related concerns pertaining to the impact of ACs on human wellbeing, health, and work efficiency have become hot topics.

Staying in an air-conditioned space all day negatively affects people's health because it deteriorates occupants' physical functions that enable them to adapt to the rhythm of the natural climate cycle [6]. Furthermore, other studies have shown that the inherent ability of occupants to combat thermal stress can be degenerated [7] and adaptive skills in terms of behavioural responses can be weakened [8]. Field studies [9] have demonstrated that the human body has a higher acceptance of the thermal environment in free-running (FR) buildings than in AC buildings, which is related to the concept of thermal adaption [10, 11]. Thermal adaption to the environment is not only good for health [12], but also contributes to energy conservation because of the wider range of accepted air temperatures [13].

Hypotheses about how behaviours affect thermal comfort and energy usage have attracted the attention of many scholars. Previous work [14-16] has found that the occurrence probabilities of occupants' adaptive actions depend on indoor/outdoor conditions and can be predicted by using logistic regression analyses. Besides, the mean outdoor air temperature of the foregoing night(s) was found to have a major impact on occupant behaviour in summer [17]. Moreover, standardized occupant behaviour profiles in energy simulation tools can be weak due to human interactions [18], and personal characteristics can have a significant impact on household decisions involving whether to use air-conditioning systems [19]. Overall, the probability of human behaviours is governed by some rules but also can be affected by many other factors.

This study focused on the behavioural and psychological responses of occupants before and after ACs became available in summer. The effect of ACs on human thermal adaption was revealed, and it is hoped that this work can serve as a scientific reference for climate responsive solutions to cooling methods that can be employed in healthy buildings.

2 Research methods

Chongqing is renowned for its hot summers, and it averages 25 days with an outside temperature of more than 35 °C in a typical year [20]. Thus, it has earned the nickname 'Furnaces' in China. Despite this, no ACs were installed in the student dormitories at Chongqing

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University until 2012. Before 2012, the only mechanical cooling equipment installed was ceiling air fans. This provided an opportunity for us to conduct a comparative study of subjects' (occupants) responses before and after the ACs were installed. Because of the age of the subjects, building structure, outside environment, and the fact that the interior fitment had not changed much over the years, this site was better than other types of buildings for a long-term study. Illustrations of the dormitories are shown in Figure 1.

The field studies were conducted in the summers of 2008 and 2016. The psychological wellbeing and behavioural responses of occupants to the thermal environment were investigated through a questionnaire sent to students living in the dormitories. During the eight years of the study, the building structure did not change, which means that the natural indoor and outdoor environment can be treated as not having changed much.

The first survey was conducted between 27 June and 8 September 2008 by delivering approximately 650 copies of the paper questionnaire during daytime, and 573 valid copies were collected in 9 days. The second survey was conducted between 24 June and 15 July 2016 by sending online questionnaires to smart phones, and 428 valid copies were collected in 15 days. The total sample sizes met the requirements for a 90% confidence coefficient with a sample error of less than 5% using simple random sampling. To avoid unacceptable errors, days for which less than 20 students responded were not used to analyze the probability of behavioural responses. The outside thermal parameters came from the Shapingba meteorological station of the China Meteorological Administration (Site No. 57516) [21], and the data were collected on sunny, cloudy, and rainy days during the surveys.

a **b** **c**

Fig. 1. Illustrations of the dormitories: a) Outside, b) inner part, and c) plane sketch.

The questionnaire was comprised of the following three parts: background information, subjective evaluation, and behavioural responses. Environmental satisfaction was evaluated on a five-point scale by asking 'How do you feel about the thermal environment in your dormitory: very satisfied (+2), satisfied (+1), indifferent (0), unsatisfied (-1), and very unsatisfied (-2)'. Thermal sensation was assessed by using the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) seven-point thermal sensation scale [22]: cold (-3), cool (-2), slightly cool (-1), neutral (0), slightly warm (+1), warm (+2), and hot (+3). The SBS questions in this study were based on the 32 types of SBS recommended by the U.S. Environmental Protection Agency (EPA) [23], and questions were adjusted according to the actual situation.

During the same time, the use of ACs and fans and the opening of windows based on occupants' self-reports were recorded. Furthermore, the following question was asked to probe occupants' preferred behaviours: 'Which measurements would you take to improve indoor thermal conditions?'

3 Results and analysis

3.1 Occupants' wellbeing

3.1.1 Environmental satisfaction

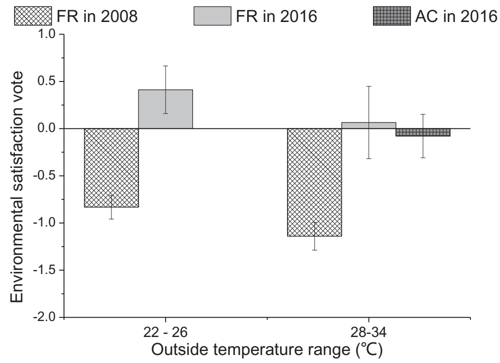

Fig. 2. Mean environmental satisfaction vote for different outside temperature ranges

Figure 2 shows the mean environmental satisfaction vote (ESV) for the following two outside temperature ranges: 22–26 °C (neutral) and 28–34 °C (warm). The ESV increased from about -1 (unsatisfied) to 0 (indifferent) after the ACs were made available in 2016. Moreover, the ESV was even better during neutral outside temperatures (22–26 °C) after the ACs became available in 2016 than that when ACs were not available in 2008. This means that the available ACs significantly improved occupants' wellbeing regardless of whether the equipment was used or not, which could be attributed to higher perceived control [24] and a better thermal experience [25].

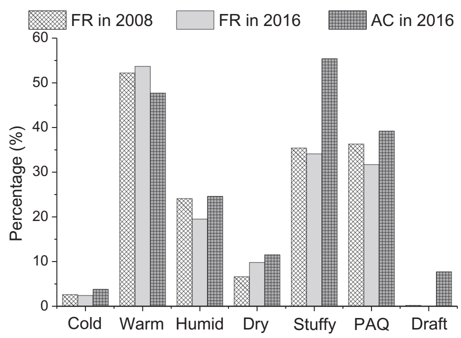

Fig. 3. Reasons for being unsatisfied

Figure 3 shows the main reasons for being unsatisfied with the environment, which included being too warm or stuffy, bad perceived air quality (PAQ), and high humidity (>20%) in all cases. Additionally, the data show that a higher proportion of occupants felt stuffy and experienced draughts when the ACs were used.

3.1.2 Thermal sensation vote

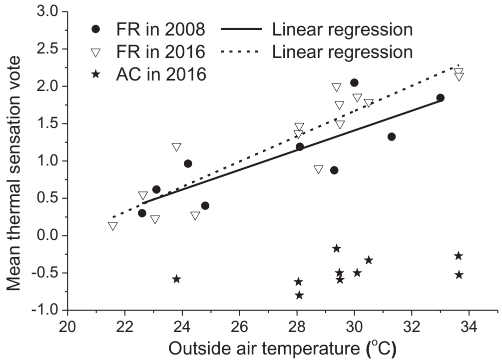

Fig. 4. The mean value of the TSV with the outside temperature

Figure 4 shows the thermal sensation vote (TSV) relative to the outside temperature. When ACs were used in 2016, occupants felt slightly cool and barely affected by the outside temperature. When ACs were not available in 2008 or not used in 2016, there were no significant differences in the TSV relative to the outside temperature.

3.1.3 Sick building syndrome

Table 1 provides the self-evaluation results for SBS during the survey. The prevalence of SBS was much lower among those who did not use the AC in the 2016 survey, which could imply that occupants who were not using the ACs were perhaps more accommodative to the warm thermal environment or that the environment created by AC use may increase the prevalence of SBS. Through an odds ratio (OR) analysis of the data in 2016, AC use was found to be a risk factor in the prevalence of SBS (OR = 1.184 (0.995, 1.409)), in which being absent-minded (OR = 1.53), eye discomfort (OR = 3.22), and discomfort in the upper respiratory tract (OR = 2.58) were significantly affected by AC use.

Table 1. The prevalence of SBS in 2016.

SBS	dizzy	nausea	fatigue	sleepy	absent-minded	eye	URY	skin	difficulty breathing
FR (%)	5.1	1.7	15.8	21.5	9.0	2.8	3.4	4.5	3.4
AC (%)	6.9	2.4	18.5	21.1	16.4	12.9	12.1	9.5	5.6
OR (AC)	1.22	1.31	1.12	0.99	1.53	3.22	2.58	1.67	1.39
P (χ^2)	0.45	0.54	0.47	0.93	0.03*	***	0.002**	0.06	0.29

Notes: *P <0.05, **P <0.01, ***P <0.001; URY – discomfort in the upper respiratory tract including dry lips, rhinobyon, or itchy throat; eye – discomfort including dry eyes, eyestrain, or lacrimation; skin – discomfort including dry skin, itchy skin, or skin disease.

3.2 Behavioural responses

3.2.1 Preferred behaviours

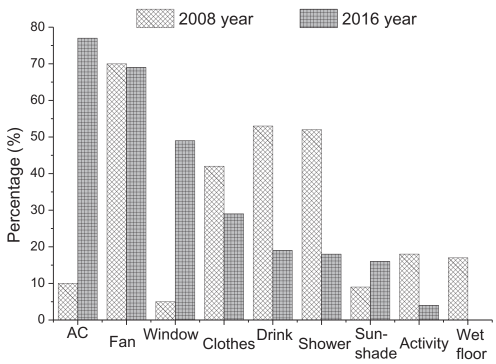

Fig. 5. Occupants' preferred behaviours

Occupants' preferred behaviours are shown in Figure 5. The most preferred behaviours in 2008 were using the fan, drinking something cold, showering, and adjusting clothing. As the window was always open, it was not a major adjustment measurement in 2008. In 2016, the most preferred behaviours were using the AC, using the fan, and adjusting the size of the window/door opening. The behaviours including drinking something cold, showering, and adjusting clothing were used less in 2016, and two behaviours, namely, sprinkling water on the floor and changing activities, were absent or low in 2016.

3.2.2 Use of mechanical equipment

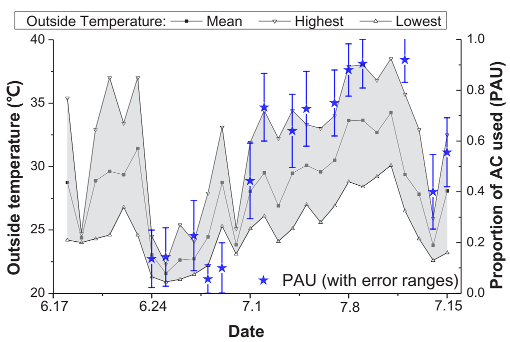

Fig. 6. Proportion of ACs used and outside temperature with time during the survey in 2016

Figure 6 illustrates the proportion of ACs used (PAU) relative to outside temperatures on different days during the survey in 2016. As shown, the PAU was highly related to the outside temperature. During the survey in the summer of 2016, the average temperature of the AC was set at 26 °C (41%), 25 °C (26%), and 24 °C (18%). Furthermore, the AC was mainly used at night and at noon.

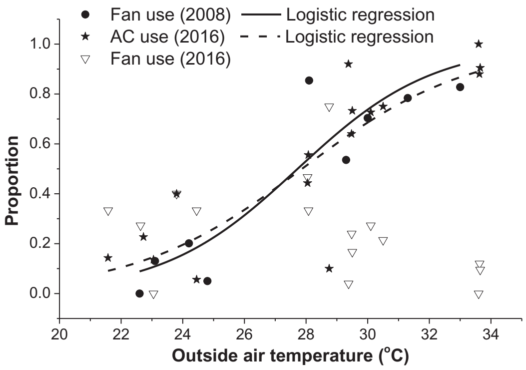

Fig. 7. Proportion of mechanical equipment used relative to outside temperature

Figure 7 shows the proportion of fans used (PFU) and PAU on different days alongside the outside temperatures in 2008 and 2016. Logistic regression analyses revealed that the relationships between the probability of a behaviour and outside temperature were as follows:
PFU in 2008:

$$PFU = e^{(-12.59+0.45t_{out})}/[1+e^{(-12.59+0.45t_{out})}];$$

$R^2 = 0.82$ (1)

PAU in 2016:

$$PAU = e^{(-10.19+0.37t_{out})}/[1+e^{(-10.19+0.37t_{out})}];$$

$R^2 = 0.72$ (2)

The PFU in 2016 did not change according to the outside temperature because the primary cooling method was an AC at that time in the summer. Therefore, only a proportion of occupants used the fan.

3.2.3 Non-mechanical adjustments

The typical clothing ensemble included short pants with a short sleeve shirt, with a mean clothing insulation value of about 0.3 clo. No significant difference was found for the different conditions.

Figure 8 shows the proportion of windows opened (PWO) in different conditions. The PWO was highest in 2008, when 91% of occupants opened the windows. When ACs were made available in 2016, the PWO was 82% during the free-running period, and it dropped to 13% after occupants started using the ACs. This was because the opening of windows when the AC was used would have caused more energy to be consumed and increased the electric bill.

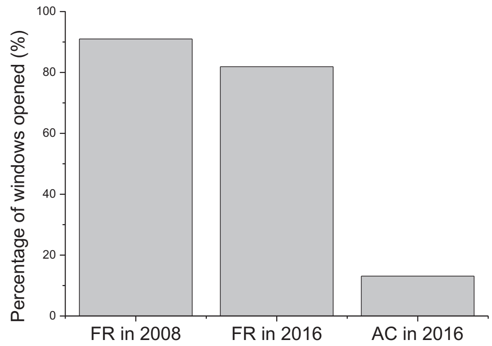

Fig. 8. Proportion of windows opened

4 Conclusions

This paper evaluated occupants' adaptive behaviours and wellbeing in a hot climate before and after the availability of ACs. The following advances and problems were identified:

The most preferred behaviours were using the AC after it became available, followed by using the fan and adjusting the size of the window/door opening. Before that, occupants demonstrated more variety in their behaviours such as drinking something cold, showering, adjusting clothes, sprinkling water on the floor, and changing activities.

The PAU in 2016 and PFU in 2008 demonstrated a logistical fit with the outside temperature. The PFU in 2016 remained at a low level, and it did not change much with the outside temperature.

The main reasons for being unsatisfied with the environment were being too warm, feeling stuffy, perceived bad air quality, and high humidity (>20%). After ACs were installed, occupants' environmental satisfaction vote was higher, and the TSV remained at slightly cool.

When ACs were used, a higher proportion of occupants felt stuffy (54%) and experienced draughts (38%), while a lower proportion of windows were opened (13%); moreover, when ACs were used, more occupants reported being absent-minded (OR = 1.53) and experiencing eye discomfort (OR = 3.22) and discomfort in the upper respiratory tract (OR = 2.58). An analysis of the TSV revealed that the ability of thermal adaption weakened after the ACs were installed.

Thus, althogh the indoor comfort is improved by air conditioner, the indoor air quality in air conditioning sapce should pay more attention in the furture .

Acknowledgements

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References

1. Brager, G.S. and R.J. de Dear, *Thermal adaptation in the built environment: a literature review.* Energy and Buildings, 1998. **27**(1): p. 83-96.
2. Wang, J., et al., *Sick building syndrome among parents of preschool children in relation to home environment in Chongqing, China.* Chinese Science Bulletin, 2013. **58**(34): p. 4267-4276.
3. Li, B.Z. and R.M. Yao, *Building energy efficiency for sustainable development in China: challenges and opportunities.* Building Research and Information, 2012. **40**(4): p. 417-431.
4. Zhai, Y.C., et al., *Human comfort and perceived air quality in warm and humid environments with ceiling fans.* Building and Environment, 2015. **90**: p. 178-185.
5. Schiavon, S., et al., *Thermal comfort, perceived air quality and cognitive performance when personally controlled air movement is used by tropically acclimatized persons.* Indoor Air, 2016.
6. Zhu, Y., et al., *Dynamic thermal environment and thermal comfort.* Indoor air, 2016. **26**(1): p. 125-37.
7. Wang, Z.J., et al., *Human thermal physiological and* psychological *responses under different heating environments.* Journal of Thermal Biology, 2015. **52**: p. 177-186.
8. Liu, J., et al., *Occupants' behavioural adaptation in workplaces with non-central heating and cooling systems.* Applied Thermal Engineering, 2012. **35**: p. 40-54.
9. Liu, H., et al., *Seasonal variation of thermal sensations in residential buildings in the Hot Summer and Cold Winter zone of China.* Energy and Buildings, 2017. **140**: p. 9-18.
10. de Dear, R.J. and G.S. Brager, *Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55.* Energy and Buildings, 2002. **34**(6): p. 549-561.
11. Yao, R., B. Li, and J. Liu, *A theoretical adaptive model of thermal comfort - Adaptive Predicted Mean Vote (aPMV).* Building and Environment, 2009. **44**(10): p. 2089-2096.
12. Yang, Y., et al., *A study of adaptive thermal comfort* in *a well-controlled climate chamber.* Applied Thermal Engineering, 2015. **76**: p. 283-291.
13. Nicol, J.F. and M.A. Humphreys, *Adaptive thermal* comfort *and sustainable thermal standards for buildings.* Energy and Buildings, 2002. **34**(6): p. 563-572.
14. Rijal, H.B., et al., *Using results from field surveys to predict the effect of open windows on thermal comfort and energy use in buildings.* Energy And Buildings, 2007. **39**(7): p. 823-836.
15. Haldi, F. and D. Robinson, *On the behaviour and adaptation of office occupants.* Building and Environment, 2008. **43**(12): p. 2163-2177.
16. Andersen, R.V., et al., *Survey of occupant behaviour and* control *of indoor environment in Danish dwellings.* Energy and Buildings, 2009. **41**(1): p. 11-16.
17. Schweiker, M. and M. Shukuya, *Comparison of theoretical and statistical models of air-conditioning*-unit *usage behaviour in a residential setting under Japanese climatic conditions.* Building & Environment, 2009. **44**(10): p. 2137-2149.
18. D'Oca, S., et al., *Effect of thermostat and window* opening *occupant behavior models on energy use in homes.* Building Simulation, 2014. **7**(6): p. 683-694.
19. Kim, J., et al., *Understanding patterns of adaptive* comfort *behaviour in the Sydney mixed-mode residential context.* Energy & Buildings, 2017. **141**: p. 274-283.
20. Li, B., et al., *Climatic Strategies of Indoor Thermal* Environment *for Residential Buildings in Yangtze River Region, China.* Indoor And Built Environment, 2011. **20**(1): p. 101-111.
21. Administration, C.M., *The ground climate data of China :Shapingba meteorological station, http://data.cma.cn* 2016.
22. ASHRAE, *ASHRAE standard 55-2013: thermal environmental conditions for human occupancy*. 2013, ASHRAE Atlanta (USA).
23. EPA, *Search Terms (Contains): sick building syndrome*. 2012.
24. Luo, M.H., et al., *The underlying linkage between personal control and thermal comfort: Psychological or physical effects?* Energy and Buildings, 2016. **111**: p. 56-63.
25. Velt, K.B. and H.A.M. Daanen, *Thermal sensation and thermal comfort in changing environments.* Journal of Building Engineering, 2017. **10**: p. 42-46.
26. Kalmár, F., *Investigation of thermal perceptions of subjects* with *diverse thermal histories in warm indoor environment.* Building and Environment, 2016. **107**: p. 254-262.
27. Nicol, F. and M. Humphreys, *Derivation of the adaptive equations* for *thermal comfort in free-running buildings in European standard EN15251.* Building And Environment, 2010. **45**(1): p. 11-17.