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Impacts of Variations in Air Conditioning System Set-Point Temperature on Room Conditions and Perceived Thermal Comfort

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Abstract

This paper describes research carried out to investigate specific features of the operation of air-conditioning systems of University buildings in Hong Kong. Changes in thermostat set points were introduced so as to investigate the impact on conditions experienced and also to determine spatial variations within the rooms. Measurements of environmental conditions were made at 5 minute intervals over a total investigation period of 6 days. Concurrently with the environmental measurements occupant surveys took place, the subjects being a group of postgraduate students. Some 912 sets of survey data were accumulated and this was used in conjunction with environmental data to compare actual and predicted sensation votes. Comparisons of sensation votes and preference votes were also carried out. Main findings were: that a significant degree of temperature variation occurred across the rooms despite the sets of controllers being used in conjunction with each other to effect changes; that the relationship between actual and predicted sensation votes exhibited a degree of variation between days even with the same occupants and that occupants tended to vote over a wider range than was predicted; and that there was a clear (as expected) inverse relationship between actual sensation and preference voting.

Keywords: thermal comfort; temperature variation; air-conditioning; controls; Hong Kong

1 Introduction

In certain climates air-conditioning systems have become almost ubiquitous; sometimes because of necessity and sometimes because of occupant expectation. The energy consumption associated with use of air-conditioning is a feature of both modern life and modern buildings, and the resulting peak demand requirements can have substantial impacts on electricity supply systems. There is also concern that occupied and space conditioned spaces may exhibit issues with negative reaction from occupants when operated outwith suitable ranges – for instance: too warm in winter; and too cold in winter (see for example Mendell and Mirer, 2009). Further, in order to deal with present and impending problems of global climate change, any steps available to reduce carbon dioxide-generating energy use should be taken. The question then remains how to minimise the demand for air-conditioning whilst maintaining the required degree of comfort. Part of dealing with this conundrum is to understand better how air-conditioning systems are used in practice and how they perform when perturbations are introduced; evidence suggests this is less than optimal (Sekhar, 2016).

As a result of these concerns, studies have been undertaken to elicit information on how well systems perform when variable influences exist, such as shifting of thermostat set-points. These studies can also help to answer questions about occupant perception and reaction to changes in air-conditioned conditions. Several studies of this topic have been carried out (such as Boerstra, Loomans and Hensen, 2013) though none in detail for this particular building situation. In the longer term, understanding of this issue could also help determine how different, perhaps 'smart' systems could be used to enhance air-conditioning control (see Cheng and Lee, 2014).

This paper reports results of recent field studies carried out in Hong Kong. The subjects of the studies were University students, most newly arrived in Hong Kong from different parts of China. No single previous climatic background was predominant amongst the group. This student course group has been investigated in previous years but for different purposes and results presented at the NCEUB Windsor Conference (Pitts, 2014).

The buildings of Hong Kong are largely air-conditioned and during the periods of study in the later summer, external conditions generally require substantial use of air-conditioning to achieve comfort. The rooms used in this study were located in buildings completed in the last 6 years and both had won awards for sustainability.

A particular reason for choosing a location such as Hong Kong is both the number of thermal comfort studies performed there over the years (see for example Mui and Chan, 2003) and also because there has been evidence to suggest cooling systems are operated at lower temperatures than might be expected to cope with a combination of occupant expectation and the higher clothing insulation levels often worn (Chan et al, 1998).

The aims of the study were several-fold:

a. To examine how changes in the thermostat settings in the rooms impacted upon conditions produced in the rooms and potential variations in thermal conditions between different points within the rooms.
b. To determine the comfort reactions of the student groups over several days given a situation in which the conditions set by the thermostats were changed.
c. To examine if the students exhibited any degree of tolerance to environmental conditions which might be outside their normal comfort envelope.
d. To compare between days and between rooms to check if any patterns of reaction were evident.

2 Locations Studied

The two rooms investigated were both lecture rooms and both had similar furniture: moveable bench style desks and plastic chairs with no padding. The buildings used were adjacent, separated only by a University campus service road. Both had similar air-conditioning systems with thermostatic controllers placed in groups on one wall of each room – significantly perhaps the walls for the thermostats were those opposite to the windows. The air-conditioning air supply and extracts were integrated into the ceilings with supply air adjacent to the light fittings and spread evenly across the whole of each space. Solar heat gain was minimised during the course of the study by drawing down fabric blinds on the windows – in one case this consisted of a double set of screens to minimise influence.

Room 1 had approximate dimensions of 10m. x 7m.; room 2 was larger at approximately 8m. x 12m. Each room had standard fluorescent type lighting systems. Floor to ceiling heights was approximately 2.8m. Some windows were openable but all remained closed during the course of the surveys as external temperatures exceeded 30°C with very high humidities.

Figure 1 shows a panoramic photo of one of the rooms in which the surveys were carried out.

Figure 1. View of Room 1.

3 Environmental Surveys

The well-known Hobo data loggers were used to monitor temperature and humidity in the rooms being surveyed. These devices use simple measurement transducers which can lead to variations between individual sensor measured values. In order to check for calibration purposes, all devices to be used were placed in an isothermal location and left to reach equilibrium at two different temperatures before and during the tests. The variations in measured values over periods of several hours was evaluated and though variations did exist – typically of 0.1°C for test periods (though occasionally larger), there was no discernible pattern and no specific logger which seemed to be measuring temperatures at an offset to the mean. For measurement of relative humidity larger variations could be expected due to the nature of the measurement transducers and it was decided that a check was required for variations of larger than ±2% r.h. (representing up to 4% variation between sensors); however agreement was surprisingly consistent between readings from the loggers under the same conditions as mentioned above. In calibration tests for the 2014 study only one logger consistently produced values more than 2% different to the average value (which was corrected for in the analysis) and in 2015 all loggers appeared to register within 2% of the average so no adjustments were made.

Thermal conditions were measured at 10 points in 2014 and 7 points in 2015 in each of the spaces. Temperature and humidity data were collected at 5 minute intervals using a rectangular grid distribution across each room: in 2014 a 3 x 3 grid spread of data loggers was used with an additional measurement point at the front of the room; in 2015 a 3 x 2 spread of loggers was used again with an additional logger at the front of the lecture room.

It was not possible to measure mean radiant temperature or air velocity at the individual points however the air movement (caused principally by the air-conditioning system) was established to be fairly uniform by spot checks. Mean radiant temperature could not be measured continuously but spot readings suggested it could be estimated as the air temperature plus 1°C. The lack of continuous measurement of these two parameters is an area which could be prescribed for further study should sufficient equipment is made available in the future.

4 Occupant Surveys

The study was carried out with two different groups of students: one in 2014 and one in 2015. Each year two rooms were surveyed on sequential days when occupied by those students whilst undertaking classroom activities. Though some of the activity consisted of sitting listening to lectures there was a substantial amount of task activity meaning movement between locations and slightly elevated metabolic rates. In each room three days worth of surveys were completed (one in 2014, two in 2015) giving a total of six days of data. There were more females (typically 75%) in each group than males but these data were not collected as part of each individual survey. The majority of students surveyed were between 22 and 25 years of age. There was no obligation to complete the survey and some of the individual surveys produced fewer sets of results as students were either preoccupied with other tasks or simply chose not to take part.

The survey process utilised was that each day the groups of students would be invited to respond on several occasions to the comfort survey questionnaire. At each time point the questionnaire asked them to provide the following details:

1. Clothing information from which to estimate clo values;
2. Their position within the room so as to determine the most appropriate set of environmental measurements to be used;
3. Information on activity level just prior to the completion of the survey, from which to estimate metabolic rate;
4. Sensation vote on ASHRAE 7-point scale;
5. Preference vote on 5-point scale;

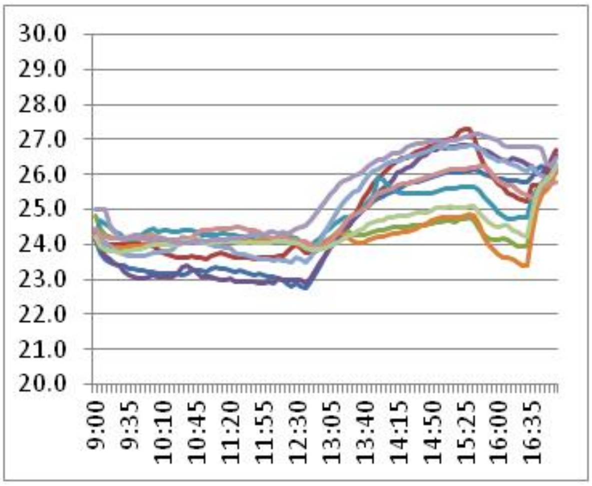
Several surveys were carried out each day numbering between 4 and 7 per day, with 23 to 41 students completing each survey depending on the year, class size and other factors (mentioned above). In total 912 timed survey response sets were collected.

5 Variation of Control Settings and Impact on Thermal Environment

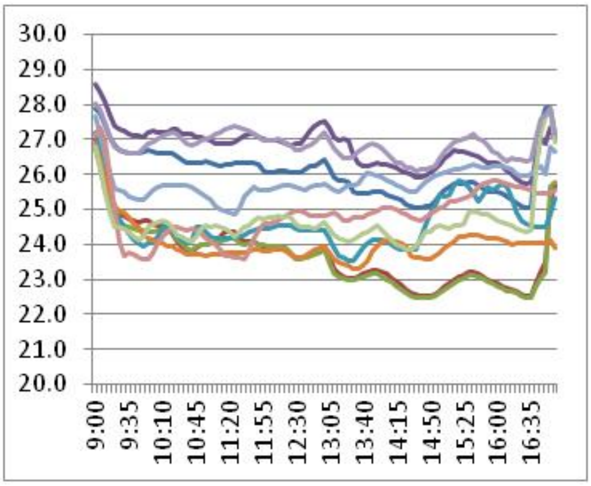
The control thermostats in the University rooms were available for staff and students alike to modify in response to conditions. The systems were also programmed only to operate at times that the rooms were expected to be occupied.

Each or the survey rooms had a number of thermostat/controllers – in each case they were positioned in groups (typically of 3) adjacent to each other. In 2014 neither the lowest or highest temperature that could be set was limited – at least in terms of the control setting – however in practice tests before carrying out the assessment it was observed that the actual conditions could not reach the more extreme values. In 2015 it was observed that for some of the controllers the temperature settings available were limited to between 23.5°C and 27.5°C. This is in line with University's Energy Policy for controlling working areas in summer to 25.5°C ±2°C. The settings used on each day were defined by an attempt to create a degree of variation in order to examine reactions.

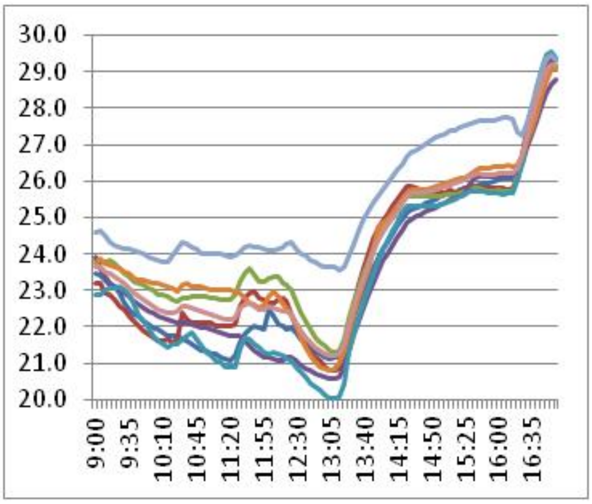
In 2014 on day 1 temperatures were set low in the morning (22°C) and high in the afternoon (26°C); and on day 2 the opposite was attempted. In 2015 on day 3 temperatures were initially set to 23.5°C but then for a short period the limits were overridden to create low temperatures just before lunchtime. In the afternoon temperatures were once again set to 26°C.



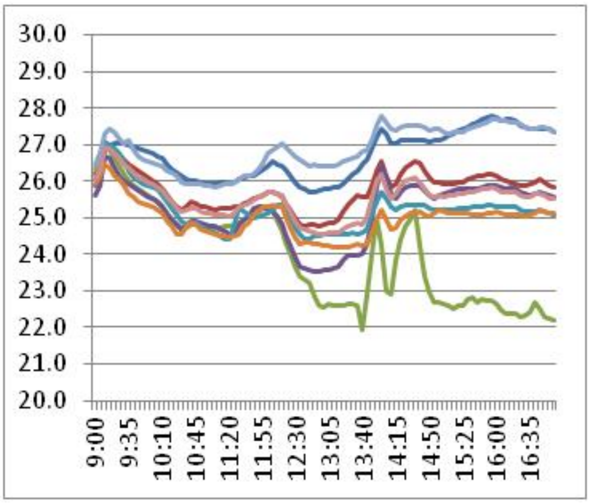
Room 1 Day 1 2014



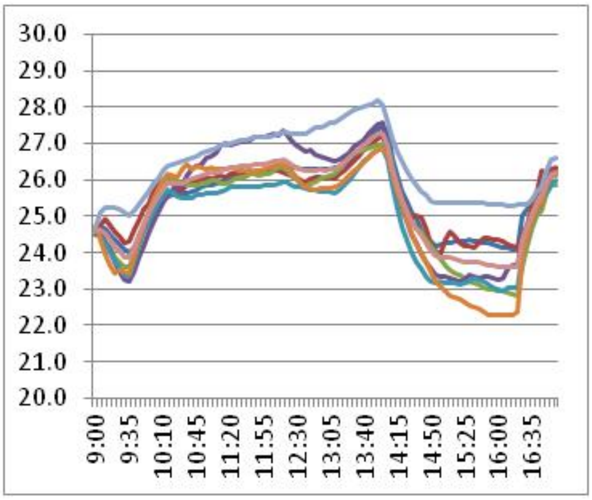
Room 2 Day 2 2014



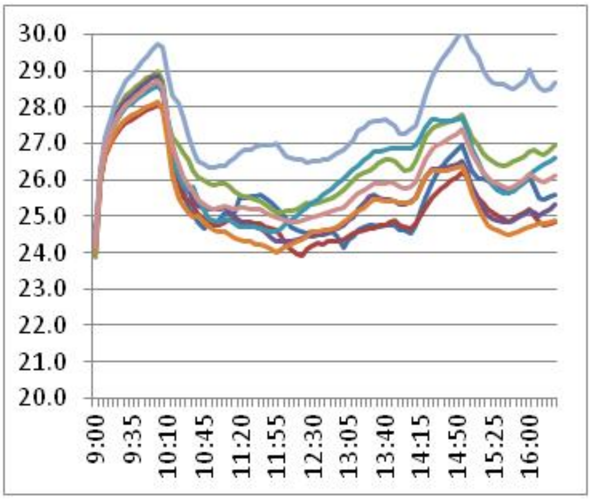
Room 1 Day 3 2015



Room 2 Day 4 2015



Room 1 Day 5 2015



Room 2 Day 6 2015

Figure 2. Temperature measurements (°C) vs. time of day at each measurement point in each room (shown as different coloured lines) – results for each survey day shown separately

On day 4 temperatures were initially set high at 27.5°C but then reduced to 25°C in the morning. At lunchtime the set point temperature was reduced to 23.5°C but then later in the afternoon back to 25°C. On day 5 a sequence of 23.5°C then up to 26°C before a short period at 27.5°C later returning to 23.5°C. Finally on day 6 the system was run at the maximum possible temperature overridden to 28.5°C for a short period before being reduced to 25°C then in the afternoon being increased to 26°C. The resulting measurements at the various locations are shown in Figure 2.

From Figure 2 one might infer several things:

a. That in both room cases (though more pronounced in Room 2) the conditions varied significantly across the range of measurement points even with the same set point being specified.
b. That room 1 seemed to have a more consistent performance that room 2.
c. That the systems seemed to operate more effectively in producing some desired temperatures as compared to others.

An inference from this might be that air conditioning control systems do not always produced the desired conditions. Another notable feature was the availability of controls within the space but with minimal instruction on how to operate. Perhaps it is assumed that knowledge of how to use is intuitive but it was not explicit which controls affected which parts of the room, hence the choice to vary all in unison. The only evident information was the details of the University Policy to operate systems within certain limits to control energy use.

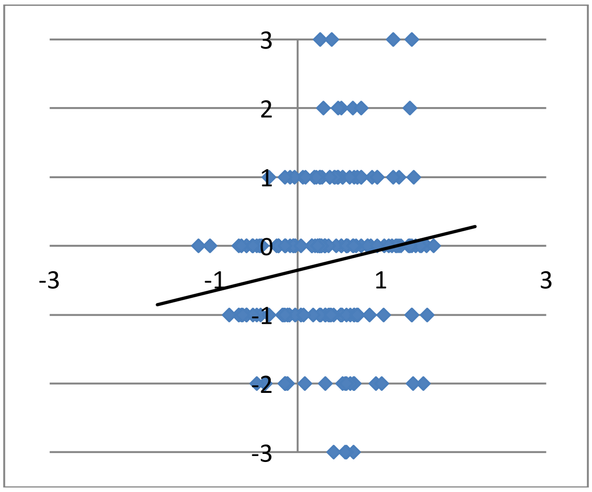
6 Sensation: Comparison of Actual and Predicted Votes

Actual sensation votes were collected for the 912 surveys and compared with predicted sensation votes based on the measurements of environmental and personal variables. The predictions used the standard algorithms first developed by Fanger (1973) and reported widely in many other publications using the seven-point scale.

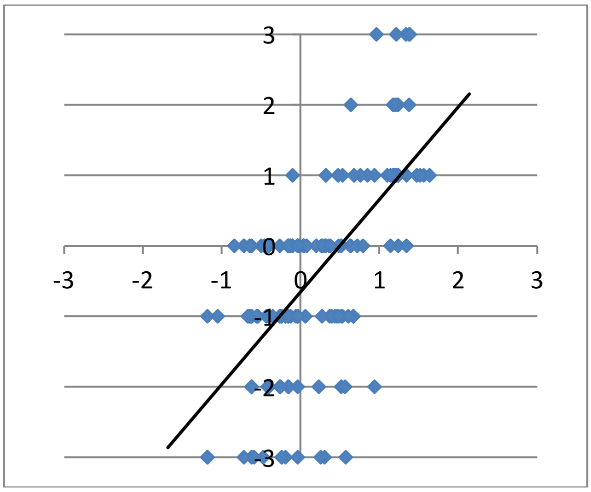
Figure 3 presents 6 charts, one for each day of the study and Figure 4 shows the combined data for all six days. From visual observation it appears that in all cases actual sensation votes recorded by the occupants had values over a wider range than the predicted values, perhaps indicating the occupants were more sensitive to the changing environmental conditions. This is at variance with some other studies which have suggested a rather 'flatter' response, i.e. that sensation votes were not as great as predicted.

The occupants did adapt by adding and removing clothing and there was certainly the opportunity to move around the rooms in order to adapt to conditions, however this does not seem to have been utilised to a great extent. The only observable (but not recorded) reason for this was the desire to sit in friendship or tasks groups.

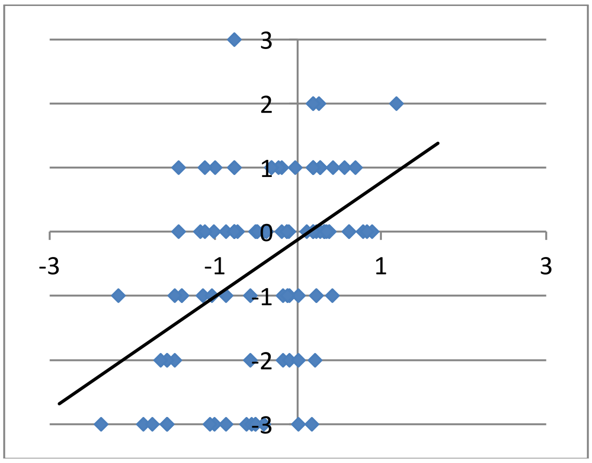
Standard linear regression analysis was performed and shown on charts for the individual days and for the whole set of data is summarised in table 1. These analyses show considerable variation in both relationship between the variables and in R^2 value. More detailed studies are suggested by this in order to consider if unexpected variations are being introduced.



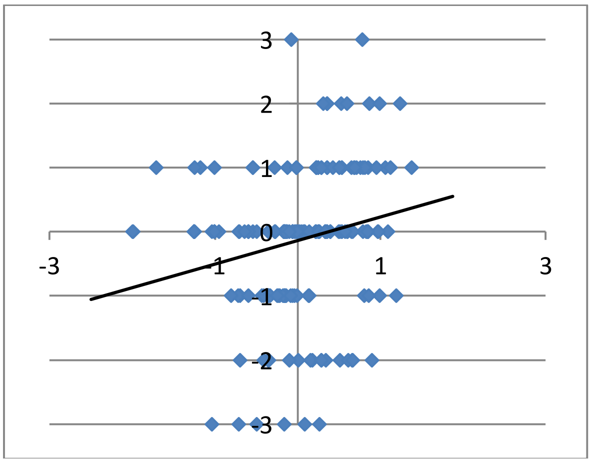
Room 1 Day 1 2014



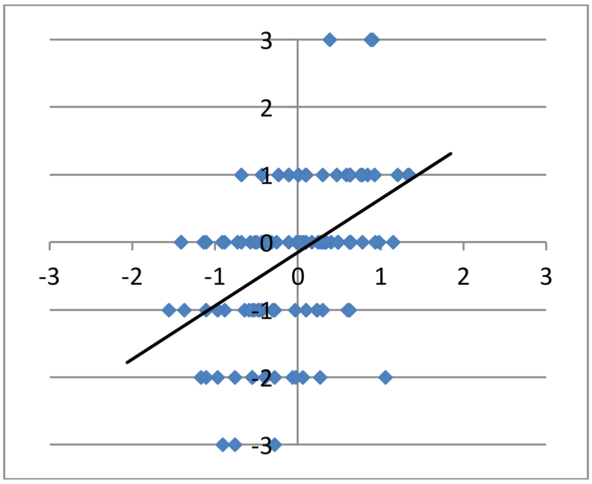
Room 2 Day 2 2014



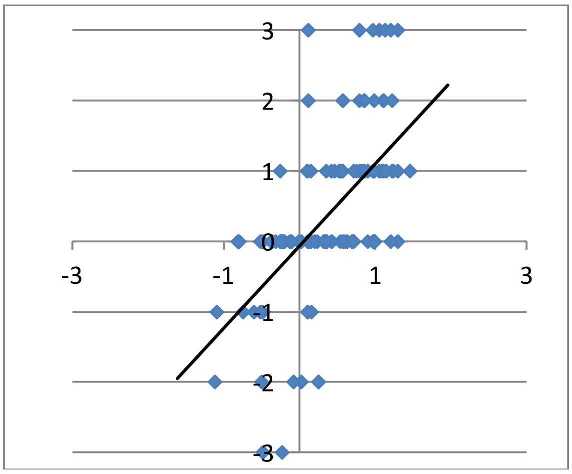
Room 1 Day 3 2015



Room 2 Day 4 2015



Room 1 Day 5 2015



Room 2 Day 6 2015

Figure 3. Occupant Sensation: Predicted Vote (horizontal axis) vs. Actual Vote (vertical axis) for each day/room (superimposed lines show least square-regression analyses)

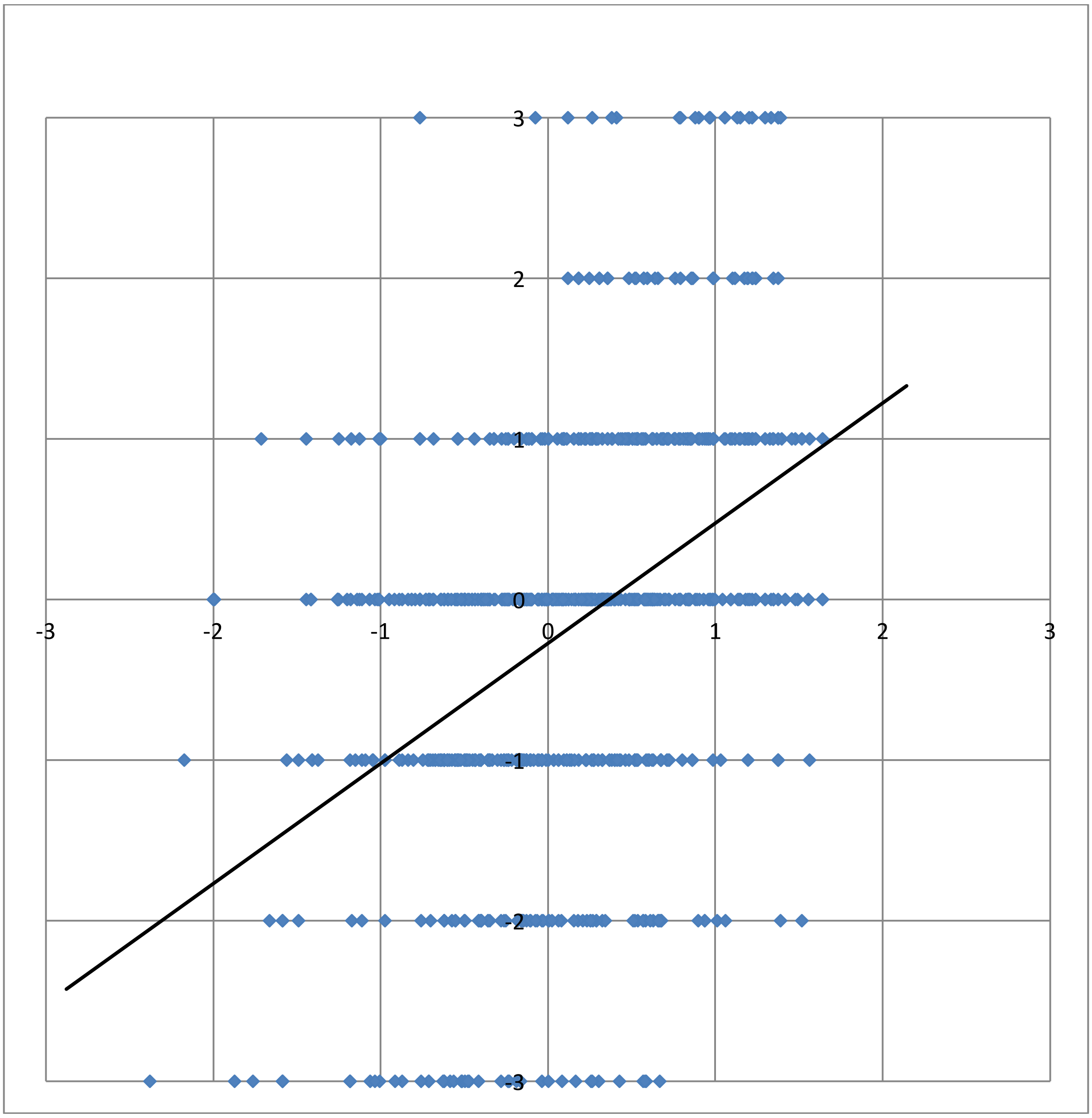


Figure 4. Occupant Sensation: Predicted Vote (horizontal axis) vs. Actual Vote (vertical axis) for all measurement days (superimposed line shows least square-regression analyses)

Table 1. Linear regression analysis for predicted vs actual sensation vote shown in graphs of figure 3 and 4

Survey day	Linear regression	R^2 value
Room 1 day 1 2014	y = 0.2947x – 0.351	0.024
Room 2 day 2 2014	y = 1.3111x – 0.6534	0.4287
Room 1 day 3 2015	y = 0.8894x – 0.1246	0.201
Room 2 day 4 2015	y = 0.3661x – 0.1388	0.042
Room 1 day 5 2015	y = 0.7919x – 0.152	0.2077
Room 2 day 6 2015	y = 1.1665x -0.0695	0.3603
All days	y = 0.7483x – 0.2723	0.169

7 Sensation and Preference

The thermal sensation felt by occupants is one of the key drivers to take action: either to adjust thermal controls for HVAC or to take adaptive actions such as changing position or clothing level. The survey recorded data on a five point preference scale (much cooler, cooler, stay the same, warmer, much warmer). This was then correlated against the seven-point sensation scale. The results are shown in Figure 5 for each day in turn.

Considering the wide variation in sensation relationships exhibited in figure 3, the preference analysis reveals more consistent relationships.

Table 2. Linear regression analysis for preference votes vs. actual sensation votes shown in graphs of figure 5

Survey day	Linear regression	R^2 value
Room 1 day 1 2014	y = -0.4462x – 0.0715	0.5207
Room 2 day 2 2014	y = -0.4320x – 0.0218	0.4929
Room 1 day 3 2015	y = -0.4413x + 0.0922	0.5461
Room 2 day 4 2015	y = -0.5334x – 0.0997	0.6859
Room 1 day 5 2015	y = -0.5007x – 0.0293	0.7042
Room 2 day 6 2015	y = -0.4601x – 0.1447	0.6108

8 Adaptation

Some adaptation by the occupants was evident in terms of clothing adjustments. These are not analysed in detail here but can be summarised as a fraction of the participants on each day that surveys were undertaken. The following data are taken from the self-reported surveys:

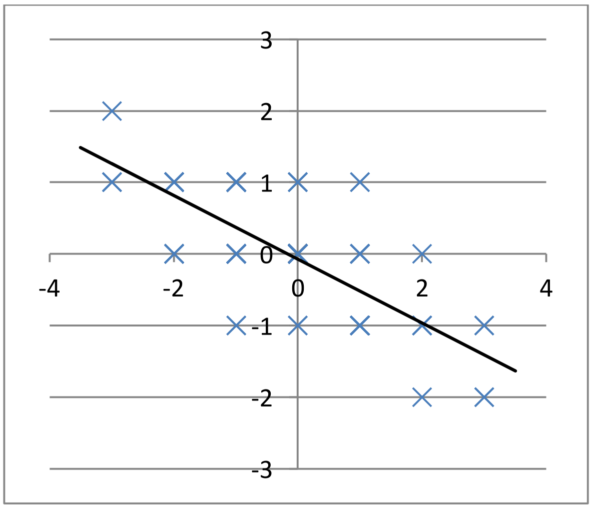
Day 1, 10 students adjusted their clothing level out of a total of 41 = 24%
Day 2, 11 students adjusted their clothing level out of a total of 37 = 30%
Day 3, 5 students adjusted their clothing level out of a total of 28 = 18%
Day 4, 9 students adjusted their clothing level out of a total of 29 = 31%
Day 5, 4 students adjusted their clothing level out of a total of 24 = 17%
Day 6, 7 students adjusted their clothing level out of a total of 23 = 30%

It should be noted that there were limits to the adaptation that was possible – simply because of factors such as social norms and modesty with regard to clothing levels. Nevertheless the data do show some reaction to changing conditions. A more complete and accurate piece of research could be suggested to analyse this issue in more depth.

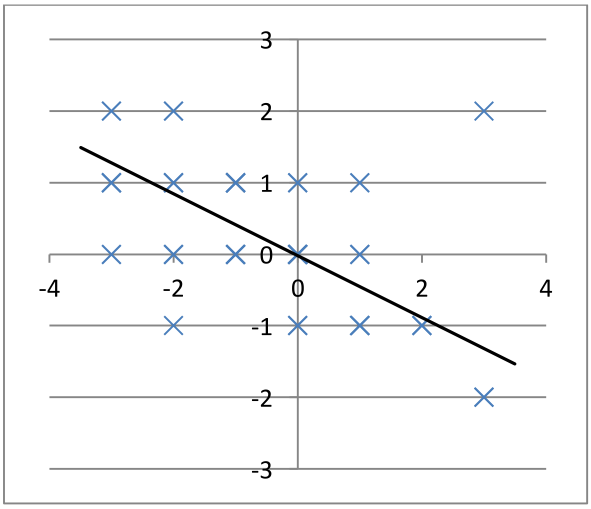
9 Discussion

The thermal sensation felt by occupants is one of the key drivers to take action: either to adjust controls or to adapt their immediate environment. Understanding the strength of that driving force is therefore very important as a route to optimising air-conditioning and the associated energy use.

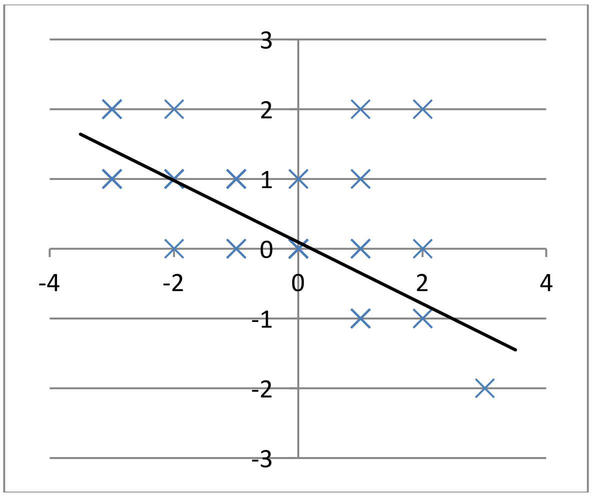
Understanding the ways in which people make such choices is also important to make design choices for the future concerning novel technologies and novel means to achieve comfort or reduce discomfort. Research work in the field is already developing (Leephakpreeda, 2012).



Room 1 Day 1 2014



Room 2 Day 2 2014



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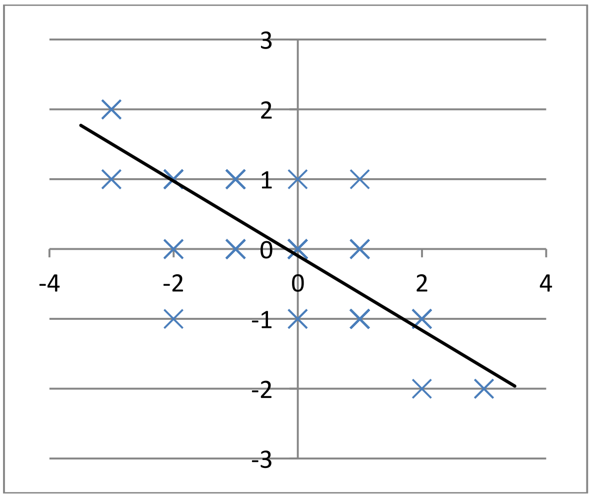

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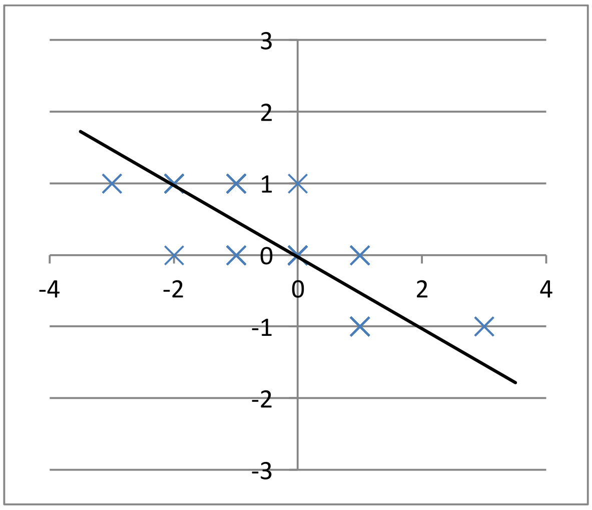
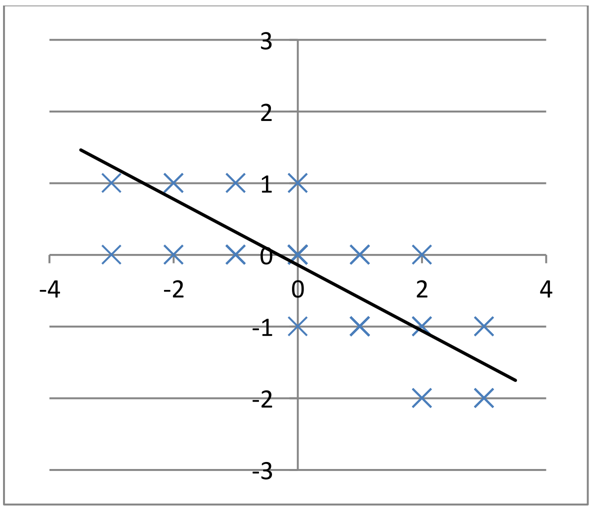


Room 1 Day 5 2015



Room 2 Day 6 2015

Figure 5. Occupant Preference (vertical axis) vs. Sensation (horizontal axis) votes from Occupant Surveys (lines show least square-regression analyses)

The results presented here indicate a number of areas in which variations occur which had not been anticipated. Firstly in terms of the conditions created and experienced across the space of the rooms investigated. The changing of the thermostat settings introduced in some cases much wider variation between points and also potentially some instability in the room being able to maintain specific conditions.
Secondly the reactions of the occupants to the experienced conditions were somewhat different to what had been expected. Variations occurred between members of the same group on consecutive days in their sensation votes, meaning perhaps there is less confidence is specifying any specific set of conditions to achieve comfort because of the individual impacts. The interlinked impact of choices about clothing level is incorporated within the analysis however the reasons for choices were not recorded.
Clearly this modest study produces more questions than it answers, but in so doing helps to identify some key areas that require research. The nature of the analyses which show differences between actual and expected performance contribute to the continuing debate about performance gaps between energy consumption predictions and actual performance.

10 Conclusions and Recommendations

The main conclusions are:

1. Temperatures set by controllers for air conditioning systems were not clearly met in the rooms to which they were attached.
2. Modification of temperature settings for temperature controllers in closed air-conditioned rooms tended to produce uneven temperature or inconsistent temperature distributions in these rooms – sufficient to create marked variations in thermal comfort sensation experienced.
3. Occupants of rooms exhibited variable correlations between actual sensed conditions and those predicted using the PMV methodology.

The thermal sensation felt by occupants is one of the key drivers to take action: to change HVAC system setting to move location; to adjust clothing; or to manipulate local environment in some other way. Several areas are therefore suggested for further research:

a. Further studies of room environments into which perturbations of control system operation have been introduced;
b. Research into interactions between air temperature and room air distribution and how this could be affected by use of non-standard or unexpected set-points
c. More detailed studies of occupants should be initiated which go beyond the basic comfort survey in order to understand better their reactions and understanding of comfort and also about how they would wish to access and use control systems.
d. Contribution of the system performance issues in these circumstances can also be investigated in relation to identifying the impacts in variations of building systems functioning.

Acknowledgement
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