FACTORS AFFECTING 'END-OF-DAY' WINDOW POSITION IN A NON-AIR-CONDITIONED OFFICE BUILDING

Shen Wei·, Richard Buswell and Dennis Loveday

Building Energy Research Group, School of Civil and Building Engineering

Loughborough University, Loughborough, LE11 3TU, United Kingdom

Corresponding author:

Tel.: +44 (0)7545 479329; Fax: +44 (0)1509 223981; E-mail: S.Wei@lboro.ac.uk

Abstract

This paper presents a longitudinal study observing people's use of windows in mixed mode cellular offices, and sets out to identify factors other than air temperature, that have a significant influence on window operation. The work focuses on the final position of the window at the end of the working day. The results have been compared to other published work and the building is found to have similar characteristics when it and its occupants are treated as a whole. When sub-sets of the data are examined, the factors of season, floor level, gender, and personal preference emerge as having a statistically significant effect on the end-of-day window position in the building examined and these findings are properly discussed with relevant references.

Keywords: Non-air-conditioned building; End-of-day window position; Window behaviour; Gender; Floor level; Personal preference.

1. Introduction

In non-air-conditioned buildings, occupants are able to adjust their indoor environment by using available adaptive opportunities such as opening a window or adjusting clothing [1]. Most studies in this field focus on occupants' operation of windows, since the window connects the internal and

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Corresponding author – Tel.: +44 (0)7545 479329; Fax: +44 (0)1509 223981; E-mail: S.Wei@lboro.ac.uk

Post-Publication – Tel.: +44 (0)1509 223783; Fax: +44 (0)1509 223981; E-mail: R.A.Buswell@lboro.ac.uk

external environments and has a significant impact on both the environmental conditions of a building and occupants' thermal comfort expectations in it [2].

Existing studies on occupants' window operation in office buildings mainly aimed to build a correlation between occupants' window behaviour and their surrounding thermal environment. Therefore, environmental factors such as indoor air temperature [3, 4] or outdoor air temperature [5-8] or a combination of them [9, 10] were proposed to be the main 'driver(s)' for occupants to open/close their windows. In addition, some non-environmental factors were also identified to have an influence on the window state, such as the previous window state [6, 10, 11], time of day [6, 10, 11], occupancy pattern [6, 10], season [6], floor level [10], personal difference [4, 9, 10] and building orientation [7]. However, most above studies focus on occupants' window use during working hours, and therefore, *"the behaviour of the occupants' towards night ventilation is generally poorly understood."*[12].

This study focuses on the end-of-day window position that directly influences the use of night ventilation in non-air-conditioned buildings. Existing studies on occupants' window behaviour at the end of the working day were mainly based on thermal factors such as indoor [3] or outdoor air temperature [6, 10], and these have generated useful models for use in building simulation. However, it is also possible that there are other factors that could affect this behaviour, and understanding of these issues is less well developed. Individual occupant behaviour or the behaviour of a particular group of individuals within a building population may vary. Furthermore, people's determination of their end-of-day window positions could also be dependent on times of year, or season. Developing a better understanding of these non-environmental factors could influence decisions about building layout, systems design, building control and occupant education. This paper investigates the significance of a number of these non-environmental factors on a case study building in the UK.

2. Building Description

This study was carried out in the building that houses the School of Civil and Building Engineering at Loughborough University, UK (52°45'54''N, 1°14'15''W, alt.70m). Figure 1 depicts the Southwest façade of the building, and shows a typical office. The building is an 'L' shape with cellular offices around the perimeter, all of which have nominally the same floor area (10.2m^2). Each window shown in Figure 1 belongs to an individual office. Although the outside of the building is curved, there are essentially only two facades, one facing Southwest and one Northwest. The exterior of the building is covered by a mesh, which is designed to both shade the façade and provide a degree of security on the ground floor, allowing windows to be left open with reduced risk of theft. Each office has a door opposite the window, the door opening onto communal spaces on each of its three floors, with all floors connected via a full height atrium.

Figure 1: The case study building (left) and a typical office (right).

Typical office occupation is nominally 9:00am-5:00pm, with each office being occupied by the same person hence promoting a sense of 'ownership' of each office by its occupant. Occupancy varies significantly between individuals throughout the year, due to several factors that include teaching, research meetings and off-site visits. Often, absence from, and presence, in the office are not routine and at particular times in the year the building occupancy decreases, most notably in August, which is when most staff have less commitments and hence is a popular period to take a summer vacation. Over the winter holiday break in December/early January, the building closes for about 10 days.

Each occupant has sole control over the environmental conditions in his/her office and typical adaptive opportunities are: window and door position, a window blind position and temperature control for a dedicated radiator (operative during the heating season). The building is mixed mode, supplying additional ventilation in the summer through swirl vents mounted in the floor of each office. Heating during winter is provided by a hydronic heating system, serving each office, and typically is switched on during the first week in October and switched off at the end of April, with some variation due to ambient temperature and work scheduling of the estates staff. The heating switch-on period usually coincides with the end of the daylight saving period in the summer months, when the UK operates on Greenwich Mean Time (GMT) +1hr.

3. Method

The aim is to investigate whether non-environmental factors could influence window behaviour in the building, with a focus on the end-of-day window position due to its influence on overnight ventilation and hence on building thermal performance and energy use the following day.

A case study approach was selected so that occupant presence, activity and other data could be observed and monitored in detail over a significant period. Data were gathered over three 'seasons', accounting details about the building heating operation and daylight saving in the analysis.

Many surveys investigating window behaviour have been carried out using differing numbers of individuals: Haldi and Robinson [10] collected their data from 14 south-facing offices located on three floors and occupied by either one or two occupants; Yun and Steemers [11] carried out their study in 6 offices with differing numbers of occupants, night ventilation strategy, building type, window orientation and window type. The challenge for these studies was to understand the limitations of the data and minimise confounding factors to establish the significance of the results. The work reported in this paper is based on 36 offices, and 36 occupants. A systematic approach has been adopted here to analyse the data, eliminating the effects of the key environmental factors and then to explore the non-environmental effects on window position by using subsets of the data. As a result the data are presented in three principal sections that i) identify the dependence on outdoor air temperature; ii) explore the effects of the non-environmental factors; and finally, iii) explore the classification of the data by personal preference. In each section, the details of the analysis approach taken are presented, together with a set of results and a discussion. The remainder of this section describes the detail of the data collection method and the notion of the 'sample-day', which is a fundamental unit on which the analysis is based.

3.1 Data collection

A total of 36 offices and the associated office occupants participated in the study. Three observation periods were defined and these were classified by season as summer, transitional (or swing), and winter. Table 1 gives the precise dates for the data collection together with other key dates in the operational cycle of the building. It should be noted that the actual sequence of the observation periods was summer – winter – transitional, taking place over two years. There is an overlap between the winter and transitional periods. This is because the winter period is defined here as the period when the heating system is on and the national time is set to GMT. The summer period is defined as the period when the heating system is off and the national clocks are set to daylight saving. One month either side of the daylight changing was considered to be the transitional period, and the data for this period was purposefully collected either side of this point.

Table 1: Observation periods and key dates.

Observation Periods		Key Dates	
Summer	20/07/2010 to 20/09/2010	Heating switch on	03/10/2010 and 04/10/2011
Winter	01/11/2010 to 26/03/2011	Daylight saving ends	31/10/2010 and 30/10/2011
Transitional	10/10/2011 to 20/11/2011	Winter building closure	24/12/2010 to 04/01/2011

During each observation period, the indoor air temperature was measured every 10 minutes by a Hobo UA-001 temperature sensor (±0.5°C), located under the occupant's desk at the abdomen level, avoiding direct sunlight. This temperature measurement at one height was considered adequate, since thermal comfort was not the primary focus of the work. Additional measurements made during the transitional observation period used a Hobo U12 sensor attached to a shelf in the office, about 600mm above desk level. This measured air temperature (±0.35°C) and globe temperature, the latter via a Hobo TMC1-HD temperature probe (±0.25°C) surrounded by a blackened, 40mm table-tennis ball. The globe sensors thus created were calibrated against a manufactured 40mm Grant globe sensor (±0.2°C) and were shown to give measurements within 0.2K. Weather data were recorded using a Delta-T WS-GP1 weather station located on the roof of the case study building.

Due to the flexible working hours, to determine occupants' presence and end-of-day window positions, the approach was personal observation by the experimenter. The observations were carried out at three times every day: 10:00am, 11:30am and 3:00pm, which maximised the chance of capturing presence. If occupancy was observed at any of these times, then occupant presence for that working day was recorded. The end-of-day window position (or window position on departure) of each office was noted by a further observation at 8:00pm when most occupants had vacated the building (on a typical day).
In the case study building, most departures from the work place occurred between 3:00pm and 6:00pm and hence the outdoor air temperatures at these times were recorded. Averaging these values (the difference of temperatures at these two time points is typically less than 2K) gave a good estimate of the external air temperature at the time when occupants would have left their offices for the day, and this is the value of outdoor air temperature used throughout the analysis (the same as for the analysis of indoor air temperature).

3.2 Calculation of sample-days

The analysis throughout has been based on the notion of a 'sample-day'. Each seasonal observation period was made over a number of days, n. The sub-scripts, n_w, n_s and n_t denote the total number of days of observation in each of the winter, summer and transitional (swing) seasons, respectively. A sample-day is defined as the number of potential opportunities for any window under observation to be found either opened or closed at the end of any one day during the observation period; an office must be occupied at some points during the day to provide actuation of the window; hence if an office is occupied for 3 days out of 5, the sample-day count for that period would be 3. There is no distinction made between one office being occupied for 2 days and 2 offices being occupied for only one day; both would yield a sample-day count (n') of 2. The sample-day count has been used to calculate a value for ϕ, defined as the proportion of windows left open on departure, using,

$$\phi = n'_{open} / n' , \tag{1}$$

where n'_{open} is the number of sample-days where windows were left open on departure. A total of 36 people (in 36 offices) were observed over 72, 30 and 81 working days in summer, transitional and winter observation periods, respectively, i.e. $n_s = 72$, $n_t = 30$, and $n_w = 81$. The total number of sample-days for each period was $n_s^{'} = 1360$, $n_t^{'} = 292$ and $n_w^{'} = 1842$.

The outdoor air temperature, t_{ao}, has been demonstrated to be a strong indicator of window operation in a number of studies [5-10] as well as this one, and so has been adopted here as the driving variable against which ϕ is plotted in all cases.

4. Results

Sub-sets of the total seasonal sample-day data set were used to analysis individual factors of interest (occupant gender, floor level etc.). In order to estimate confidence in the results, the sample-day data were classified by binning the data in discrete 2K intervals of t_{ao}, as used by other researchers [13]. Each temperature bin contained at least 30 sample-days and at least 80% of the people in the study were represented in each bin.

4.1 Dependence on outdoor air temperature

To compare window opening behaviour with previous studies that related this to outdoor air temperature, the data points in the left hand plot of Figure 2 show the relationship $\phi = f(t_{ao})$ observed in the study; the mean bin value for t_{ao} is used and the 95% confidence intervals are calculated by the Adjusted Wald Method [14]. This demonstrates that the proportion of windows left open on departure is generally proportional to the outdoor air temperature, as expected. The solid line overlaid on these data is the output from a logistic regression model given by,

$$\phi_{model} = e^{a+b\cdot t_{ao}} / (1 + e^{a+b\cdot t_{ao}}) \ , \qquad (2)$$

where the coefficients a and b are estimated using maximum likelihood (for the model presented in Figure 2, $a = -4.09$, $b = 0.155$, $R^2 = 0.074$). Equation 2 had also been used by Haldi and Robinson ($a = -2.47$, $b = 0.121$) [10] and Rijal et al. ($a = -2.76$, $b = 0.181$) [9] to model their data, and both are reproduced in Figure 2. In Figure 2 (right) all three models are plotted over a wider temperature range, showing the S-shape characteristic of logistic regression models. The characteristics generated by the model presented in this paper have been extrapolated, indicated by the dotted line, with the region of the model where data were available highlighted by the solid line. It is also worth noting that in the UK Midlands, temperatures above 30°C are rare in summer.

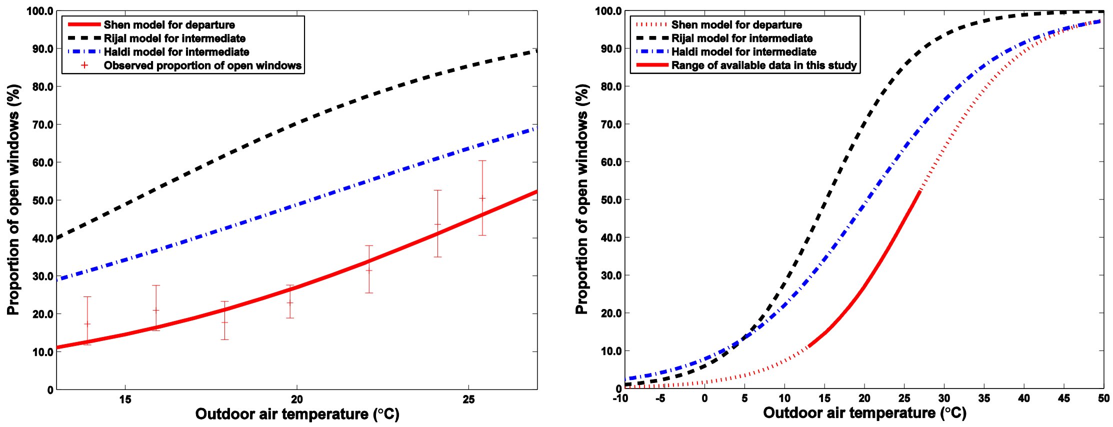


Figure 2: Proportion of windows open as a function of outdoor air temperature; Comparison of the data gathered in this study and the work of others.

It can be seen that the observed behaviours from all three studies are broadly similar in terms of their relationship with t_{ao}. This provides evidence that the building under observation in this study is not significantly different from other buildings. One important difference, however, is that both Rijal et al. and Haldi and Robinson published observations based on window operation during normal working hours, as opposed to the end-of-day when people are departing the work place, as is the case in this study. It might be expected, therefore, that a higher probability of windows being closed at the end of the day would be observed.

4.2 The influence of non-environmental factors

Non-environmental factors that could potentially impact on end-of-day window positions were placed into five classifications as shown in Table 2.

Table 2: Classification of factors that have the potential to affect end-of-day window positions.

Classification	Factor	Classification	Factor
Environmental	Outdoor air temperature	**Building**	Façade orientation
	Indoor air temperature		Floor level
Seasonal, 'cultural', policy	Seasonal change	**Individual**	Gender
	Change to daylight saving time		Personal preference
Operational	Absence in subsequent days		

The classification introduced here provides a framework, within which window use behaviour can be investigated. It is entirely conceivable that an individual's personal preferences and habits, which have developed over a lifetime of social interaction and experience of living with a particular physiology, can have impact on their behaviour [15, 16]; the operational management of the work place has the potential to influence where people are located in the building and to determine the nature, type and freedom to follow own work preferences and dictate movement from workspaces, and absences from the office [17]; the design of the building itself has an impact on the environmental factors to which individuals are exposed [18, 19]; season will affect many factors in a naturally ventilated or mixed-mode building such as the indoor environment [20], occupants' thermal comfort [21], clothing insulation [22] and occupants' window use during the daytime as well [6], and could therefore affect the end-of-day window position in commercial non-air-conditioned buildings.

Eliminating the confounding factors in this investigation is difficult, and as demonstrated in the previous section, the strong dependency of window operation on t_{ao} is ever-present. Accordingly, each factor considered is plotted as a function of t_{ao}. Where certain factors have demonstrated a significant influence on ϕ, then the internal air temperature, t_{ai}, is brought into the analysis to identify whether this could be an influencing factor on the result and is discussed as appropriate. Seasonal changes have been investigated by comparing data from the summer and winter observation periods. A more detailed consideration of the possible influence of change from daylight saving time is also carried out using the data from the transitional observation period. Building and operational factors are explored using sub-sets of the data from the summer observation period. Where significance was observed, the winter data are also presented for completeness. Finally, the ‘individualistic’ factors are considered. Since the age range of the building occupants in the study is mainly between 35 and 55 years, age has not been considered as part of this study. Gender and personal preference, however, are treated. The results are presented here in a particular sequence for clarity, but have been subject to a number of iterations in order to sub-divide the data sets in such a way as to minimise unwanted influences from other factors.

Logistic regression analysis, commonly used in studies of occupant window use behaviour, defines the probability of a specific event happening (windows left open overnight), under different conditions. The predictor variables can be either numerical (e.g. temperature) or categorical (e.g. gender, floor level, facade and personal preference), or a combination of both. The *Wald statistic test* is the most commonly used approach to evaluate the contribution of specific predictors in the logistic model, and is defined as: the maximum likelihood estimate of the coefficient of each predictor divided by its standard error. The asymptotic distribution of the *Wald statistic* is chi-square with degrees of freedom equal to the number of parameters estimated. If the *P-value* of a predictor variable from the *Wald statistic test* is less than a critical value, such as 0.05 for the 95% confidence level, then it implies that this variable makes a contribution in the model. For a categorical predictor (e.g. gender), a significant *Wald statistic* reflects that from the statistical viewpoint, a behavioural difference exists between the groups (e.g. males or females) that are classified by this categorical predictor. For each factor investigated in the following sections, the *Wald statistic* and the corresponding *P-value* are given to show the statistical significance of effect of that factor on the end-of-day window position. Sometimes, the *Wald statistic test* might fail to reject the null hypothesis for specific predictors, especially when the sample size is small. Therefore, all the results of the *Wald statistic test* provided in the later analysis had been examined by the *Likelihood ratio test*, another statistical approach testing the contribution of individual predictors in the logistic model.

4.2.1 Seasonal effects

The sample-day count from the male-occupied offices on the first and second floors, from both facades was utilised to maximise the available data (avoiding any potentially confounding effect of gender and the ground floor). Data from summer and winter were used to compare the seasonal differences. In order to remove the effects of outdoor air temperature, the same temperature bins from each season were compared and are shown in Figure 3.

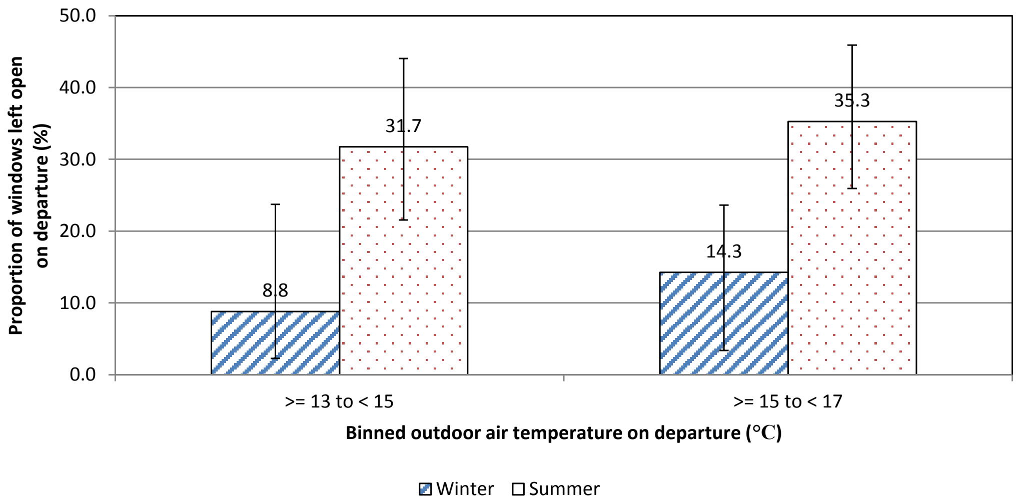


Figure 3: $\phi = f(t_{ao})$**, when the binned outdoor air temperatures in summer and winter are the same.**

The number of sample-days in each outdoor air temperature bin in Figure 3 is small and hence there is a degree of uncertainty in the data, characterised by 95% level confidence intervals included on the plot. However, the differences between summer and winter, which are bigger than 10%, appear significant (*Wald* = 13.067*, P-value* = 0.000).

Reasons for the behavioural difference between summer and winter times could be that people use windows less in winter than in summer during the working day, which has been observed by Herkel et al.[6]. There may also be influences from the reduction in the number of daylight hours; during winter in the UK it is often dark when leaving the work place. There could be a degree of energy consciousness amongst the building occupants giving them a propensity to shut windows. Whilst this discussion is largely conjecture, the important point that has been demonstrated is that it is not just the environmental conditions that affect behaviour – other factors influence people and these influences can affect the operation of a building.

4.2.2 Change of daylight saving time

Many countries, including the UK, operate daylight saving time, and so the effect of this change on the end-of-day window position was investigated. The transitional season data were used, comprised of data recorded three weeks prior to, and three weeks after, the change from daylight saving time (GMT +1hr) to GMT that takes place during October. The building heating system was on during this time. To isolate any effects from the potential confounding issue of radiant field, additional globe temperature measurements were made in a subset of the offices to identify whether there were any changes to mean radiant temperature in the space due to the 'earlier' onset of darkness affecting glazing surface temperatures. The results showed that the difference between the indoor air temperature and the globe temperature was within ±0.3°C for more than 99% of the samples (confirming close agreement between internal air and globe temperatures), and indicated that the change from daylight saving time did not induce a change in thermal comfort conditions in the offices. The data were tested for the same binned temperatures as given in Figure 3, but the differences between the GMT and the (GMT+1) data were less than 10%, these differences having no statistical merit (*Wald* = 0.365, *P-value* = 0.545).

4.2.3 Occupant absence in subsequent days

It was postulated that if an occupant knew he was going to be absent from the office for one or more days, then that might affect his end-of-day window closing behaviour, the day before the absence. Data collected from the male occupants on the first and second floors were therefore filtered to create two batches: one where each occupant was present in his/her office the following day, and the second where each occupant was absent the following day. Again, the data for both summer and winter were tested in a similar manner to the data shown in Figure 3, and no statistically significant result was found for this factor: comparing 'a normal day with presence the following day' to a 'normal day and absence the following day' was less than 5% for a given temperature range for both summer and winter times (for summer: *Wald* = 0.243, *P-value* = 0.622; for winter: *Wald* = 0.541, *P-value* = 0.462).

4.2.4 Window orientation

Zhang & Barrett [23] proposed that the window/façade orientation was another factor influencing occupants' window behaviour during working hours, due to effects from the solar radiation and prevailing wind direction. In our investigation of the case study building, however, no significant behavioural differences were found due to façade orientation during the summer time (*Wald* = 1.138, *P-value* = 0.286).

4.2.5 Floor level

Haldi and Robinson [10] proposed that occupants' window behaviour on departure on the ground floor is significantly different from those on other floors in a building. The data from our study support this conclusion as shown in Figure 4 (for summer: *Wald* = 55.018, *P-value* = 0.000; for winter: *Wald* = 13.819, *P-value* = 0.000). The data used here were collected from offices with male occupants on the three floors (avoiding any potentially confounding effect of gender). People on the ground floor close their windows in the evening more often than those on the upper floors. In this case study building, there is a noticeable difference in indoor temperatures between the offices on the ground floor and those on the upper floors throughout the year, and the first and second floors are similar in temperature (Figure 5 plotted the internal air temperature on departure as a function of the corresponding outside air temperature, separately, for summer and winter). The difference is most likely due to a combination of a slightly higher floor to ceiling height of 3.5m on the ground floor as opposed to 3.0m on the first and second floors; greater heat loss through larger windows (2.0m windows on the ground floor verses 1.6m windows on the upper floors), and cooler communal space at the bottom of the atrium which each office door opens out onto. Therefore, the cooler indoor environment in ground-floor offices at the same outdoor temperature conditions could be a reason for their occupants choosing to close more windows at the end of the working day than those on upper floors. However, when the end-of-day window position was binned according to the indoor air temperature on departure and the same statistical test between the ground & non-ground-floor offices was carried out, it was found that the difference between $\phi = f(floorlevel)$ was still statistically significant (*Wald* = 13.655, *P-value* = 0.000), hence indicating that the measured lower indoor air temperature in the ground-floor offices was not the only possible driver of the window closing behaviour.

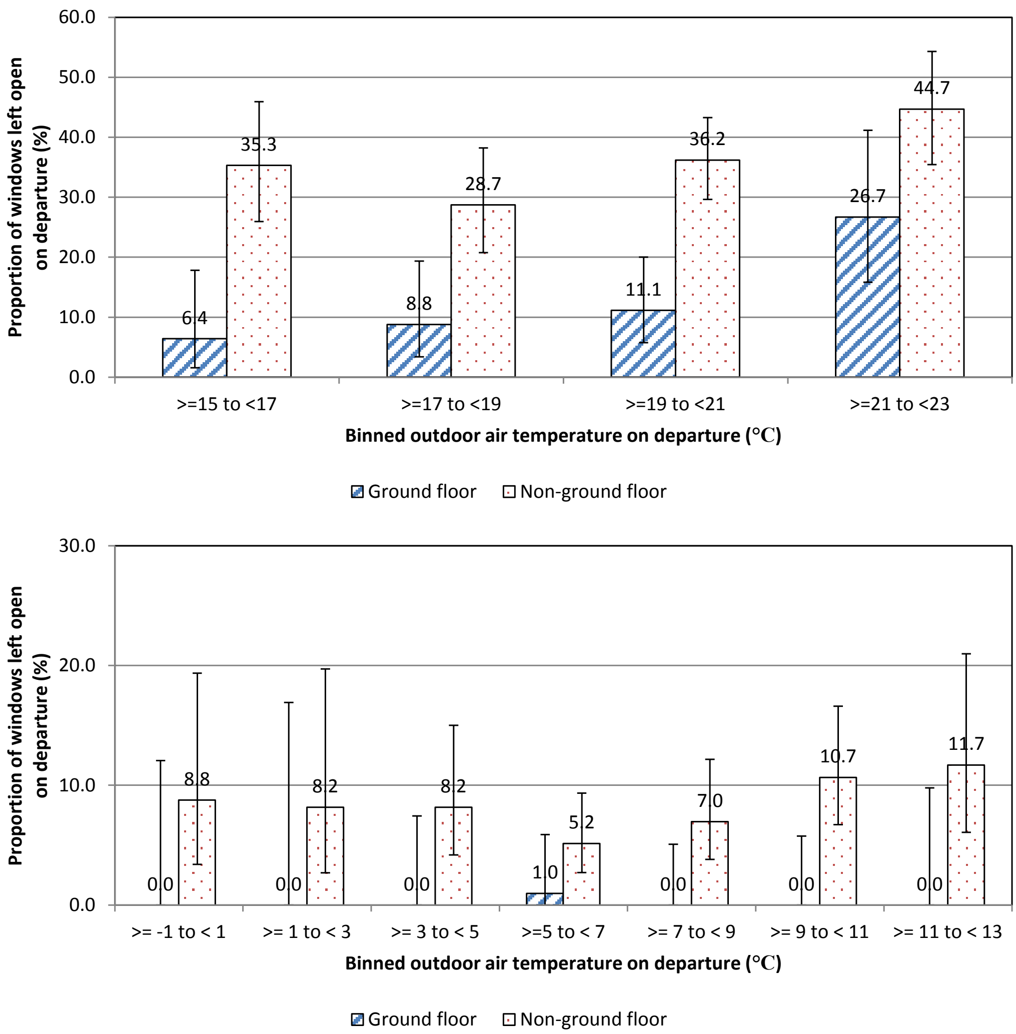


Figure 4: $\phi = f(t_{ao})$ for the ground-floor and non-ground-floor offices for both summer (top) and winter (bottom).

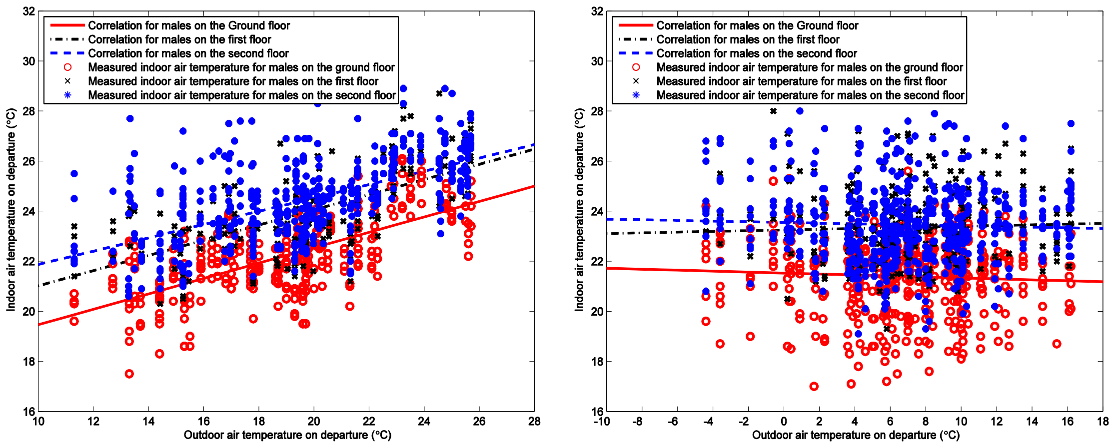
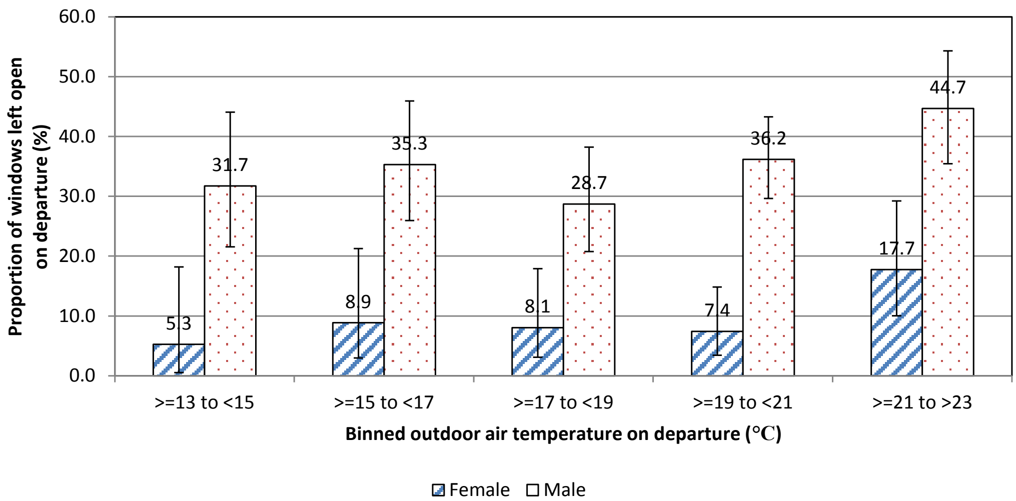


Figure 5: $t_{ai} = f(t_{ao})$ for the ground-floor and non-ground-floor offices for both summer (left) and winter (right).

It has been difficult to isolate the effects of these influences, and therefore, the conclusions drawn are that the ground floor in this building does influence window use and this appears to be caused by a combination of the indoor air temperature and potentially to a feeling of 'security', based on our observations and observations of others [10].

4.2.6 Gender

Considering the offices on the first and second floors only (avoiding any potentially confounding effect of the ground floor), 8 female and 18 male subjects were available for the study. Although the number of women is small, the possibility of gender as a significant factor was considered worthy of exploration. Figure 6 depicts the results: gender appears to have a significant impact on the window position at the end of the working day (for summer: *Wald* = 69.385*, P-value* = 0.000; for winter: *Wald* = 17.879*, P-value* = 0.000). Figure 7 gives $t_{ai} = f(t_{ao})$ and there is little difference between the internal air temperatures in the offices, and hence the internal air temperature can be considered to have no influence on this result.



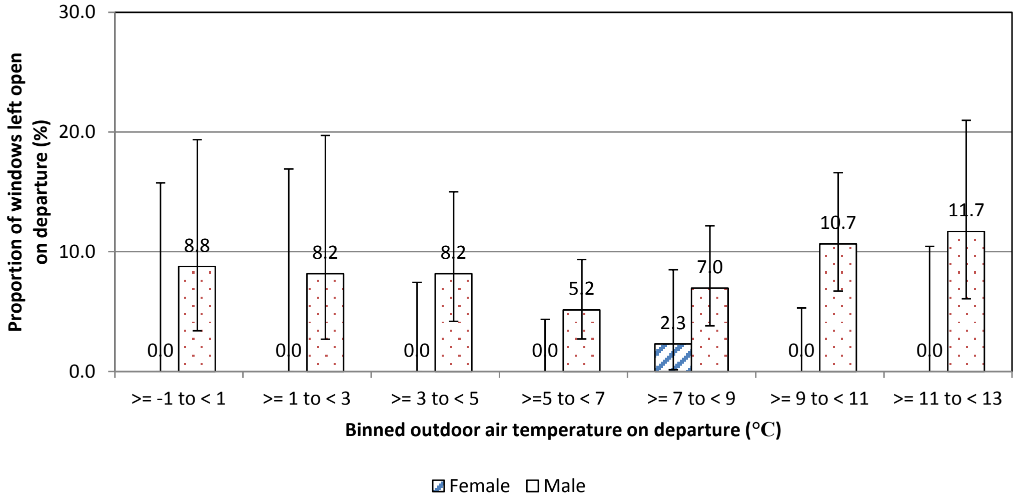


Figure 6: $\phi = f(t_{ao})$ **for differences in gender for both summer (top) and winter (bottom).**

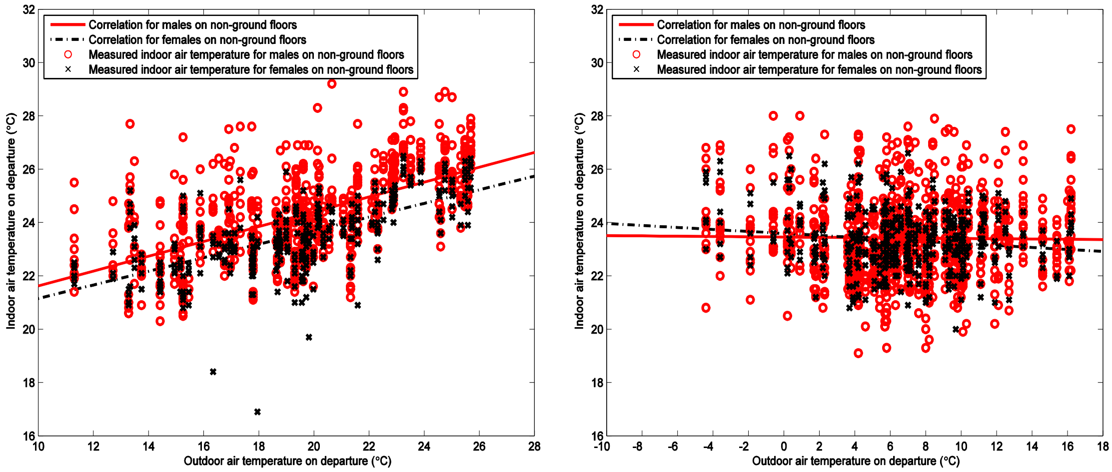


Figure 7: $t_{ai} = f(t_{ao})$ **for differences in gender for both summer (left) and winter (right).**

Previous behavioural studies support the finding that occupants' behaviour in buildings can be gender-dependent. Schweiker et al. [24] had suggested that occupants' window opening behaviour differs between male and female occupants in residential buildings, based on data measured in Japan. Fishman and Pimbert [22] proposed that, in commercial buildings, women had greater flexibility choosing their clothing insulation than men, therefore, they were able to be more tolerant of higher temperatures. Andersen et al. [25] also found that gender had effects on both use of windows and lights in Danish homes. Karjalainen [26] conducted a quantitative interview survey to analyse occupants' use of thermostats in homes, offices and in a university. Significant gender difference in the use of thermostats (females used thermostats less in households than males did) was identified in that study.

The preceding discussion would support the suggestion that the gender of building occupants may well has a significant impact on building operation and performance.

4.3 Personal preference

It was observed that there were differences in end-of-day window positions between individual occupants for both summer and winter periods: some windows were rigorously closed at the end of almost every day, whilst others would be left open across a very large range of temperature conditions, particularly apparent during the summer observation period. Differences such as these have been observed by researchers before in the summer time operation of windows at the arrival and intermediate periods of the working day [4, 9, 10]. In those studies, window users were termed 'active', 'medium' and 'passive'. These descriptors suggest that an active user is one who constantly *adjusts* the window position, whereas in our study we are more interested to see if individuals leave windows open at the end of the day, or whether they habitually close them regardless of the environmental conditions. Three new descriptors are therefore introduced here to reflect end-of-day window behaviour in the summer time. Individuals can be classified as those who: 'Habitually close' windows (observed to be largely independent of temperature); 'Leave open' windows very often (some dependency of action on temperature was observed); or exhibit a tendency to 'Adjust' windows depending on the thermal conditions (i.e. higher correlation with t_{ao}).

Based on the summer data gathered in this study, an attempt has been made to define these classes based on a notion of mean outdoor air temperature ($\bar{t}_{ao}$) and by threshold setting (θ). The approach can be repeated for other studies, so that the observed behaviours can be compared.

The mean outdoor air temperature (end-of-day) during the survey period was calculated as $\bar{t}_{ao} = 19.4°C$. The sample-days with an air temperature above this were selected to identify to which classification each individual, α, belonged. The challenge is to determine the value of the thresholds used to differentiate between the classes of users. To do this, symmetrical thresholds, θ, were used and the following rules were applied:

IF α_i is found with an open window more than $\theta\%$ of the time, THEN $n_{LO} = n_{LO} + 1$

and,

IF α_i is found with a closed window more than $\theta\%$ of the time, THEN $n_{HC} = n_{HC} + 1$

where $i = 1$ to 36 representing the number of rooms; n_{LO} is the number of users classified as one who 'leaves open' the window, and n_{HC} is the number of users classified as one who 'habitually closes' their windows. These counts are then normalised by the number of users (36 in this case), i.e. $\psi^{LO} = n_{LO}/36$ and then the proportion of the group who 'adjust' their windows is given by,

$$\psi^{A} = 1 - (\psi^{LO} + \psi^{HC}), \tag{3}$$

applying the rule IF $\psi^A < 0$ THEN $\psi^A = 0$ (i.e. IF $\psi^A < 0$, it means individuals have been counted twice). This was done for incremental values of θ and the values are plotted in Figure 8. A range of potential thresholds are indicated by the vertical dashed lines that represent the observation (some individuals leave their windows open, some leave them closed, and some vary). For the classification here, the centre of this range has been selected as $\theta = 80\%$.

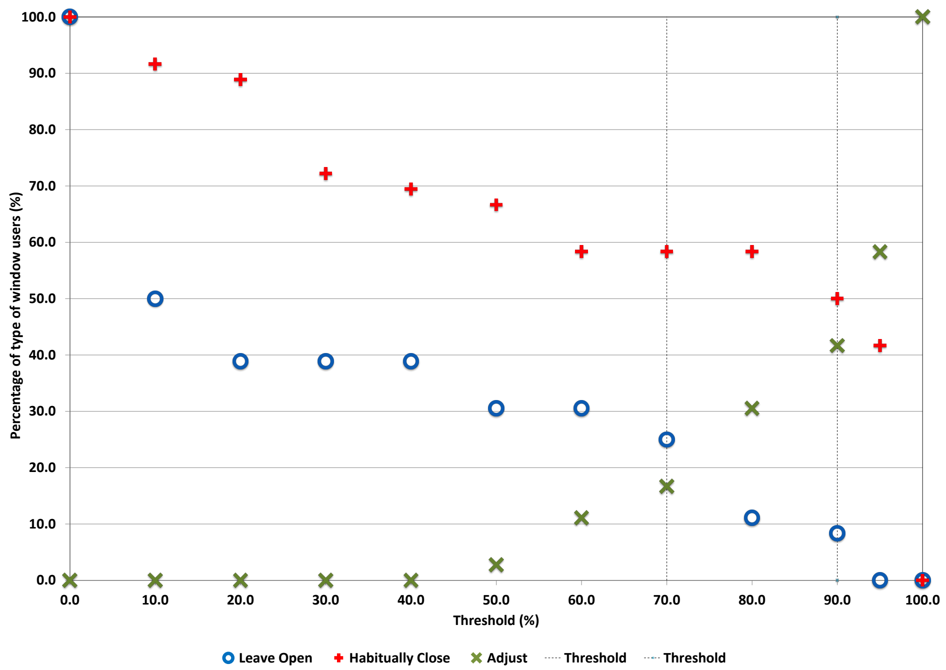


Figure 8: Threshold selection criteria.

Figure 9 shows the difference in behaviour between these types of window users for the summer time (*Wald* = 128.526*, P-value* = 0.000) using the above classifications, based only on the male subjects on the first and second floors of the building (avoiding any potentially confounding effects of both gender and the ground floor). The indoor air temperature on departure for offices occupied by different types of window users was also checked, and the difference was found to be very small: the mean difference between 'Leave Open' and 'Habitually Close' groups was 0.2K, with maximum difference of 0.3K. Therefore, this behavioural difference is proposed to be caused by individuals' personal preference, as the influences from confounding factors, such as occupant gender, floor level, indoor air temperature etc., had been eliminated in the analysis. However, whether these actions are due to intent, habit or forgetfulness is difficult to determine, but clearly a bias of one of these groups in a building could have a significant impact on the building thermal and energy performance, particular for individual offices.

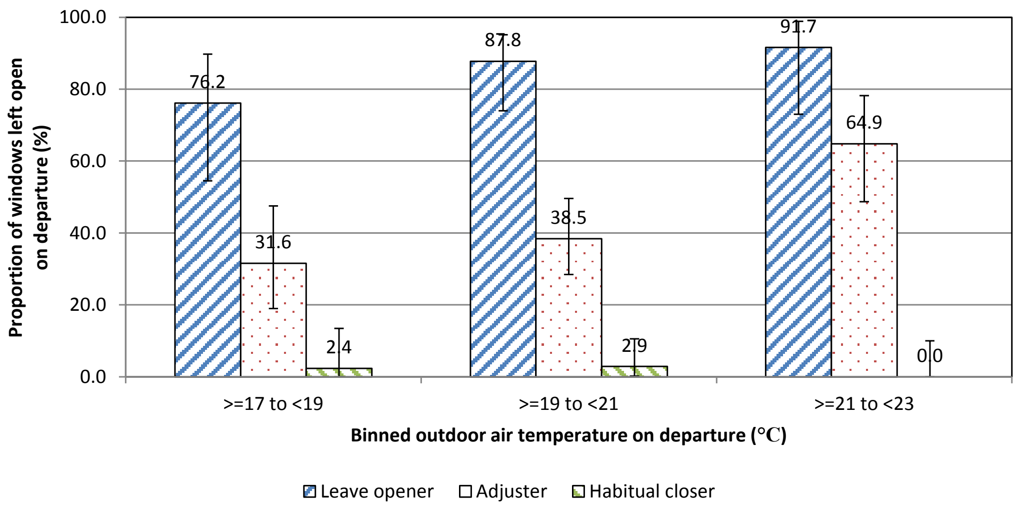


Figure 9: $\phi = f(t_{ao})$ **categorised by window user type for summer.**

4.4 Overall discussion

The preceding analysis suggests that gender, floor level, and personal preference all influence the end-of-day position of windows in addition to the environmental conditions. Gender and floor level use the classification of groups within the whole building population. Personal preference, however, uses the observed characteristics of the individual to make the classification. People of either gender, or who are members of a particular floor, were placed into the groups: 'Leave opener', 'Adjuster' or 'Habitual Closer', for the summer period, and the distribution of types of user behaviour is shown to be dependent on both floor level and gender. In Table 3 (left), the distribution of different types of users for male occupants working on different floors is shown, where a higher proportion of 'Habitual Closers' could be found on the ground floor, compared with that on upper floors. This is thought to reflect issues over security or temperature stratification, discussed previously. Table 3 (right) shows the distribution of different types of users for female and male occupants working on non-ground floors, respectively, and suggests that the females observed in the study tended to be largely 'Habitual Closers'.

Table 3: User groupings by floor level for male subjects (left) and by gender for non-ground-floor subjects (right).

Floor	Habitual Closer	Adjuster	Leave Opener
Ground	80%	20%	0%
Non-ground	39%	39%	22%

Gender	Habitual Closer	Adjuster	Leave Opener
Female	75%	25%	0%
Male	39%	39%	22%

5. Conclusions

The end-of-day window position is a key factor that can influence the energy and thermal performance of a naturally-ventilated or mixed-mode building for the following day, as well as during the unoccupied night-time period. In this paper, these window positions were observed over three seasonal periods (summer, winter and transitional) and the relationship between the end-of-day window positions and the outdoor air temperature was derived. It was established that the window behaviour within the building featured in this study was similar to those of other buildings published by other researchers. It was found that for the building studied, some non-environmental factors were observed to have a significant effect on the end-of-day window position, over and above the ambient air temperature:

- Season appears to affect the end-of-day window position. Differences were observed between the summer and winter periods and comparisons were made when the outside air temperature was the same. The reasons for this are unclear, but might be related to more regular or habitual closing of windows in the cooler days in the winter period, cooler night temperatures causing over-cooling of the room at night. Other effects may possibly be due to differences in numbers of daylight hours, or a prevalence of a more energy-conscious attitude in winter.

- Being located on the ground floor seems to influence the end-of-day window position, and as observed in other studies. This could be related to security issues, whether or not it is a perceived or real risk.
- Gender also appears to affect the end-of-day window position, with females more likely to close their windows at the end of the working day, compared with males.
- Personal preference plays a role in determining the end-of-day window position, and the distribution of types of window users is dependent on both gender and floor level.
- Daylight saving practices, occupant known absence the following day and window façade orientation showed no statistically significant effect on end-of-day window positions, for the occupants and building investigated.

The main outcome of this investigation is that there appears to be sufficient evidence to suggest that non-environmental factors may well play a role in determining the end-of-day window position, and that this merits further investigation. Should this be confirmed, there are important implications for the modelling of occupant behaviour in building simulations, as well as the possibility of incorporating occupants as unwitting agents in the management of building thermal and energy performance.

References

[1] N. Baker, M. Standeven, A BEHAVIOURAL APPROACH TO THERMAL COMFORT ASSESSMENT, International Journal of Solar Energy, 19 (1) (1997) 21-35.

[2] G.S. Brager, R.J. De Dear, Operable window, personal control, and occupant comfort, ASHRAE Transactions, 110 (Part 2) (2004) 17-35.

[3] G.Y. Yun, K. Steemers, Night-time naturally ventilated offices: Statistical simulations of window-use patterns from field monitoring, Solar Energy, 84(7) (7) (2010) 1216-1231.

[4] G.Y. Yun, P. Tuohy, K. Steemers, Thermal performance of a naturally ventilated building using a combined algorithm of probabilistic occupant behaviour and deterministic heat and mass balance models, Energy and Buildings, 41(5) (5) (2009) 489-499.

[5] P.R. Warren, L.M. Parkins, Window-opening behaviour in office buildings, ASHRAE Transactions, 90 (Part 1B) (1984) 1056-1076.

[6] S. Herkel, U. Knapp, J. Pfafferott, Towards a model of user behaviour regarding the manual control of windows in office buildings, Building and Environment, 43(4) (4) (2008) 588-600.

[7] Y. Zhang, P. Barrett, Factors influencing the occupants' window opening behaviour in a naturally ventilated office building, Building and Environment, 50 (2012) 125-134.

[8] R. Fritsch, A. Kohler, M. Nygard-Ferguson, J.L. Scartezzini, A stochastic model of user behaviour regarding ventilation, Building and Environment, 25 (2) (1990) 173-181.

[9] H.B. Rijal, P. Tuohy, M.A. Humphreys, F.J. Nicol, A. Samuel, J.A. Clarke, Using results from field surveys to predict the effect of open windows on thermal comfort and energy use in buildings, Energy and Buildings, 39(7) (7) (2007) 823-836.

[10] F. Haldi, D. Robinson, Interactions with window openings by office occupants, Building and Environment, 44(12) (12) (2009) 2378-2395.

[11] G.Y. Yun, K. Steemers, Time-dependent occupant behaviour models of window control in summer, Building and Environment, 43(9) (9) (2008) 1471-1482.

[12] V. Fabi, R.V. Andersen, S. Corgnati, B.W. Olesen, Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models, Building and Environment, 58 (0) (2012) 188-198.

[13] F.J. Nicol, M.A. Humphreys, A stochastic approach to thermal comfort - Occupant behaviour and energy use in buildings, ASHRAE Transactions, 110 (Part I) (2004) 554-568.

[14] J. Sauro, J.R. Lewis, Estimating completion rates from small samples using binomial confidence intervals: comparisons and recommendations, in: Proceedings of the human factors and ergonomics society 49th annual meeting, Orlando, Florida, USA, 2005, pp. 26th to 30th September.

[15] J.M. Carpenter, M.C. Green, J. LaFlam, People or profiles: Individual differences in online social networking use, Personality and Individual Differences, 50 (5) (2011) 538-541.

[16] V.S. Knopik, M. Alarcón, J.C. DeFries, Common and specific gender influences on individual differences in reading performance: a twin study, Personality and Individual Differences, 25 (2) (1998) 269-277.

[17] J.A. Davis III, D.W. Nutter, Occupancy diversity factors for common university building types, Energy and Buildings, 42 (9) (2010) 1543-1551.

[18] G.Y. Yun, K. Steemers, N. Baker, Natural ventilation in practice: linking facade design, thermal performance, occupant perception and control, Building Research & Information, 36(6) (2008) 608-624.

[19] H.B. Rijal, M.A. Humphreys, F.J. Nicol, Understanding occupant behaviour: the use of controls in mixed-mode office buildings, Building Research & Information, 37(4) (4) (2009) 381-396.

[20] C. Huang, Z. Zou, M. Li, X. Wang, W. Li, W. Huang, J. Yang, X. Xiao, Measurements of indoor thermal environment and energy analysis in a large space building in typical seasons, Building and Environment, 42 (5) (2007) 1869-1877.

[21] F.J. Nicol, M.A. Humphreys, O. Sykes, S. Roaf, Standards for Thermal Comfort: Indoor air temperature standards for the 21st century E & FN Spon, an imprint of Chapman & Hall, 1995.

[22] D.S. Fishman, S.L. Pimbert, The thermal environment in offices, Energy and Buildings, 5(2) (1982) 109-116.

[23] Y. Zhang, P. Barrett, Factors influencing the occupants' window opening behaviour in a naturally ventilated office building, Building and Environment, 50 (0) (2012) 125-134.

[24] M. Schweiker, F. Haldi, M. Shukuya, D. Robinson, Verification of stochastic models of window opening behaviour for residential buildings, Journal of Building Performance Simulation, 5 (1) (2012) 55-74.

[25] R.V. Andersen, J. Toftum, K.K. Andersen, B.W. Olesen, Survey of occupant behaviour and control of indoor environment in Danish dwellings, Energy and Buildings, 41 (1) (2009) 11-16.

[26] S. Karjalainen, Gender differences in thermal comfort and use of thermostats in everyday thermal environments, Building and Environment, 42 (4) (2007) 1594-1603.