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Thermal comfort: use of controls in naturally ventilated buildings

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Abstract

A field study of the thermal comfort of workers in natural ventilated office buildings in Oxford and Aberdeen, UK, was carried out which included information about use of building controls. The data were analysed to explore that what effect the outdoor temperature has on the indoor temperature and how this is affected by occupants' use of environmental controls during the peak summer (June–August). The proportion of subjects using a control was related to indoor and outdoor temperatures to demonstrate the size of the effect. The results suggest that the use of controls is also related to thermal sensation and their appropriate use is a significant part of adaptive behaviour to modify the indoor thermal conditions. The results make it possible to predict the effect of temperature on the ventilation rate in naturally ventilated buildings. © 2001 Published by Elsevier Science B.V.

Keywords: Buildings; Thermal comfort; Natural ventilation; Energy; Controls; Indoor temperature; Outdoor climate

1. Introduction

The local climate has great influence on the indoor thermal environment. The building's characteristics influence the impact of outdoor climate and play a major role in controlling the indoor thermal conditions. Their impact on thermal control of the building appears in three distinct ways [1]:

1. Transmission of the external environment through the building fabric. The building envelope modifies the transmission according to its thermal mass and insulation.
2. Transmission of solar energy and daylight through open or glazed areas. The direct transmission can be controlled by the use of blinds, curtains or glazing.
3. Infiltration of the outside air through doors and windows, cracks and holes. The use of windows controls ventilation and air movement and insulation air excluders help in reducing the infiltration.

The effects of outdoor climate can be modified by the use of various controls. The means of controlling the internal environment are usually available to building occupants. The importance of control in reducing the need for high-energy solutions has become increasingly clear [2,3]. In naturally ventilated buildings, greater control over thermal environment and ventilation could be obtained by using common means of control, e.g. openable windows, blinds and to some extent lights. The control over lighting and direct solar gain depends on the individual's control over the use of light switching and blinds.

Longitudinal and transverse surveys were carried out during a field study of the thermal comfort of workers in natural ventilated office buildings in Oxford and Aberdeen, UK. The surveys were spread over a period of 1 year. The most common means of controlling the indoor summer climate in naturally ventilated buildings in UK were available at varying scale in the buildings used for the survey. Openable windows are available in all buildings and blinds/curtains in most of the buildings. Some individuals have electric fans. The use of these controls was noted as a part of the larger comfort study in buildings. The data was analysed to explore the use of environmental controls to modify the indoor thermal conditions during summer.

The analysis shows that the use of controls plays a significant role in modifying the indoor thermal conditions. The proportion of 'open window' increases with the increase in outdoor or indoor temperature. The regression analysis of the each control on outdoor and indoor temperatures was used to demonstrate the size of the effect.

Allowing cross ventilation (window and door both open) was found to lower the indoor temperature. The effect of the availability of controls is demonstrated. Analysis of the change of use of each control was also carried out at different indoor and outdoor instantaneous temperatures and comfort votes. The results of the analysis are presented in this paper.

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2. The survey

During 1996–1997, thermal comfort field surveys were conducted in two cities in UK. One city, Oxford, is located in southern England, and the other Aberdeen, on the north-east coast of Scotland. The surveys were spread over a period of 1 year. Fifteen buildings were surveyed, nine in Oxfordshire and six in Aberdeen, 10 buildings were natural ventilated and five air-conditioned. The subjects were office workers. The study involved 909 subjects, 219 taking part in both longitudinal as well as transverse surveys, about two thirds of them in naturally ventilated (NV) buildings. Basic information about the NV buildings and number of subjects in them who were involved in the survey is given in Table 1. The buildings were a mix of heavyweight (HW) and lightweight (LW), old and newly constructed, in the private sector and in the public sector.

2.1. Longitudinal survey

The longitudinal survey obtained information from the subjects every day allowing assessment of changes in the building's environment and occupants' response to these changes. Of the 219 subjects taking part in the survey, 94 were in Oxford and 125 in Aberdeen. Each subject was asked to fill a questionnaire three to four times a day recording his thermal sensation and preference, clothing, activity and use of controls. The positions of the subjects relative to doors and windows were also noted. The thermal environment close to each subject was monitored, recording the temperature, at an interval of 15 min.

2.2. Transverse survey

The transverse survey enables assessment of occupants' response to particular environmental conditions in the building with the participation of a larger population. The survey is usually completed in 1 day, which provides a good cross section of environmental conditions. The survey involved 909 subjects — 535 in Aberdeen and 374 in Oxford. The subjects in each building were visited once a month and a questionnaire was filled for each available subject. The questionnaire carried more details than the one used in longitudinal survey. The additional questions were related to their perception about air movement, humidity, light and noise level. The finger-tip temperature of the subject was also recorded. The questionnaires were administered at the respondents' desk with simultaneous recording of the environmental variables. During the interview the questions were presented to subjects on flashcards and the responses recorded by the researcher.

2.3. Climatic data

The outdoor weather data for the period of survey was obtained from the Radcliffe Meteorological Station of Oxford University for Oxford and from a local meteorological observatory for Aberdeen. The Oxford data was recorded every 15 min, the Aberdeen data on an hourly basis. At some buildings outdoor temperature was also recorded locally. However, for the analysis, the outdoor temperatures recorded at the Meteorological Stations were used.

3. Indoor thermal conditions and outdoor temperature

Fig. 1 demonstrates the influence of the outdoor climate on indoor thermal environment. As shown in Table 2, the indoor temperature is highly correlated to the corresponding outdoor temperature. Fig. 1 and Table 2 are constructed with the data for the summer months, June–August, when the buildings will be free-running. In Britain, the heating season

Table 1
Naturally ventilated buildings surveyed with details of the subjects taking part[a]

Building code	Location	NV/AC	HW/LW (NV only)	Total subjects	Longtitudinal subjects	Transverse responses	Longitudinal responses
1	O	NV	HW	66	13	514	4181
2	O	NV	HW	33	5	196	735
3	O	AC		16	4	110	1621
4	O	NV	HW	53	10	402	1971
5	O	AC		34	8	225	879
6	O	NV	LW	17	5	143	505
7	O	NV	LW	34	9	242	1263
8	O	NV	LW	22	11	188	1626
9	O	NC	HW	99	29	761	5540
10	A	AC		85	24	371	2350
11	A	NV		83	29	389	4150
12	A	AC		100	24	430	3837
13	A	NV	LW	75	23	394	4255
14	A	NV		75	12	349	1672
15	A	AC		117	13	286	1183
Total				557	146	3578	25898

[a] O: Oxford; A: Aberdeen; NV: naturally ventilated; AC: air conditioned; HW: heavyweight construction; LW: lightweight construction.

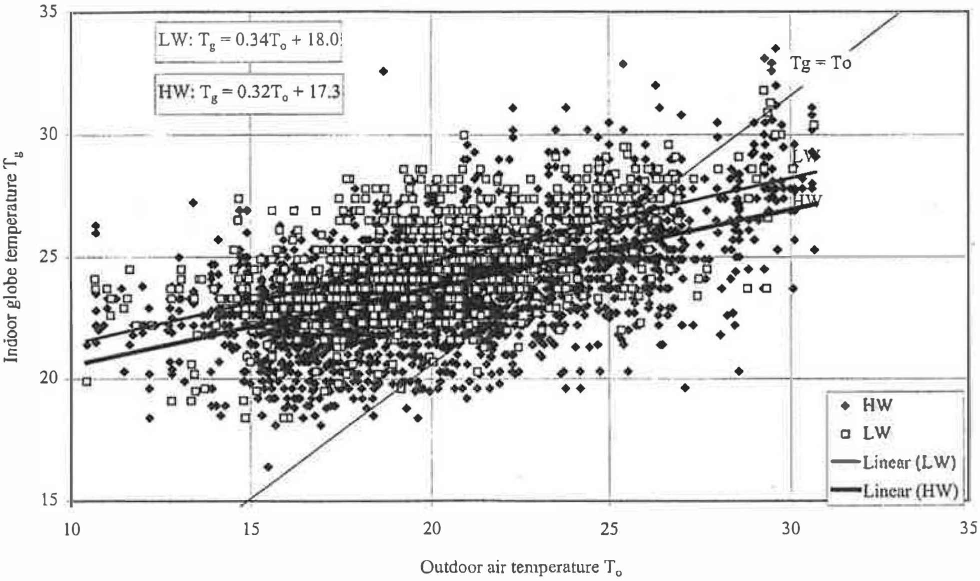

Fig. 1. Showing the variation of indoor temperature with outdoor temperature for the summer months. The regression lines show that heavyweight (HW) buildings are generally cooler than lightweight (LW) buildings.

can extend over 7 months of the year, from about October until April. There may be periods of heating in May and September and occasional breaks in heating in March and October. In this paper we are concerned with the use of controls which do not involve the use of energy, when the building is free-running.

The statistics in the table are calculated from simultaneous indoor and outdoor temperatures for times at which comfort votes were cast. The tabulated results show that indoor and outdoor temperatures are well correlated (r ranging from 0.560 to 0.688 for buildings in Oxford and 0.388 to 0.463 for those in Aberdeen). The reasons for lower correlation for Aberdeen may be the relatively a large number of missing indoor and outdoor instantaneous temperature data, which reduced the number of data set available for analysis. The values of the regression slopes suggest that the occupants are controlling the indoor conditions so that the change in indoor temperature is about one-third of that outdoors. Similar results have been presented in ASHARE RP-884 [4]. The use of controls is an important factor in explaining how thermal comfort indoors might be related to outdoor climate. Though the rate of change of indoor temperature with outdoor temperature is consistent among buildings, there is a noticeable difference in the mean indoor temperatures. In Oxford, the lightweight buildings 7 and 8 have the highest mean indoor temperatures but building 6 where the controls were fully used is an exception. Indoor temperatures in Aberdeen are not comparable because the mean outdoor temperature at 15.8°C is 4.5 K cooler than Oxford.

4. Available controls

In natural ventilated buildings the usual controls available to occupants are doors, openable windows, blinds and curtains, fans, central heating, electric or gas heaters and hot air blowers. In UK, climate heating of the building is essential during winter. However, in summer, the occupants have greater choice to control the indoor thermal environment. During the analysis for the work presented here, only the summer controls are considered.

For analysis, 'window open,' 'door open,' 'blind down,' 'fan on' and 'lights on' were coded as '1' and otherwise as

Table 2
Correlation 'r' and regression slope 'b' between instantaneous indoor temperature 'T_g' and concurrent outdoor temperature 'T_0' in naturally ventilated buildings in summer[a]

	Building	1	2	4	6	7	8	9	11	13	14
Longitudinal	Correlation (r)	0.63	0.65	0.62	0.59	0.57	0.65	0.59	0.29	0.61	0.41
	Regression slope (b)	0.37	0.29	0.30	0.41	0.30	0.35	0.29	0.16	0.41	0.24
	Mean (T_g)	24.8	24.3	23.8	23.7	25.3	25.3	23.0	23.7	23.4	23.5
Transverse	Correlation (r)	0.66	0.16	0.79	0.90	0.63	0.73	0.75	0.42	0.80	0.62
	Regression slope (b)	0.45	0.13	0.67	0.84	0.38	0.21	0.42	0.12	0.36	0.48

[a] Results from the longitudinal and the transverse surveys are shown separately.

Table 3
Discomfort and the frequency of the use of available controls in NV buildings during peak summer months

Building	Discomfort (%)	Doors (%)	Windows (%)	Fans (%)	Blinds/curtains (%)	Lights (%
1	30	59.2	75.1	27.2	19.0	39.6
2	11	–	80.6	55.1	85.7	43.3
4	35	–	69.7	62.0	06.1	54.8
6	10	66.9	40.2	17.8	40.2	74.6
7	51	60.2	66.5	17.6	04.7	69.4
8	33	75.0	70.1	47.8	27.9	83.0
9	21	76.1	78.8	22.9	07.3	98.4
11	16	60.2	70.8	19.6	19.1	77.7
13	23	75.0	54.4	31.7	26.4	84.8
14	19	76.1	11.0	80.0	05.7	79.4

'0'. The data was averaged over every 10 responses for each parameter (indoor and outdoor instantaneous temperature, comfort votes) under investigation.

5. Use of controls

A separate study [5] has shown that in NV buildings in summer the proportion of people recording discomfort is strongly correlated with the number of people who use the fans or windows and particularly ($r = 0.80$) if the two are used together. This implies that the controls are used in response to uncomfortable conditions.

The indoor climate, the outdoor climate or a mixture of the two may drive the use of controls in naturally ventilated buildings [4,5]. Opening of doors or windows enhances natural ventilation. Their simultaneous use allows cross ventilation and may cool the building if the outdoor temperature is lower than the indoor. Fans provide forced convective cooling. Blinds and curtains reduce heat gain from direct solar radiation as well as the glares.

5.1. Frequency of use

The use of available controls in various naturally ventilated buildings is given in Table 3. The table is constructed with summer data collected during the longitudinal survey If any individual has not used a control over the period und consideration (June–August) it is assumed that that part cular control is not available to the person.

In an earlier study [1], statistical analysis was made of th data for individual subjects. The percentage usage of vario thermal controls by each subject taking part in the lon itudinal survey in building 1 over the period under co sideration was evaluated. The results are tabulated in Table The table also shows the effect of the position of a subject relation to window on thermal sensation of the subje Thermal sensation is shown on Bedford scale from 1 (mu too cold) to 7 (much too warm) with comfort at around

Linear regression was used to find relationship betwe the use of a control and temperature. In the regressi instantaneous indoor and outdoor temperatures are use The controls are grouped according to their use — to cont the air movement and to reduce the solar gain/glares.

5.2. Air movement

In warm or hot weather, the rate of air movement is one the best means of improving thermal comfort. In summer open or close a door or window or to switch a fan on or of a common reaction to an environment that is either too wa or too cool. Natural ventilation can play an important role

Table 4
Use of control by the occupants in building 1

Subject code	Seating position	Outdoor temperature (°C)	Thermal sensation	Door (%)	Window (%)	Blind/curtain (%)	F ('
1.01	Away	21.0	4.75	00.0	46.0	26.4	
1.02	Away	21.5	4.88	00.0	31.0	28.9	5
1.03	Near	20.7	4.46	00.0	79.8	14.3	1
1.04	Near	19.8	4.40	00.0	83.1	29.2	2
1.05	Near	19.9	4.19	100	74.1	–	
1.06	Near	19.8	5.09	100	89.2	27.7	
1.07	Away	20.2	6.74	99.3	96.3	8.1	2
1.09	Near	21.5	4.29	33.3	100	76.2	1
1.10	Away	19.9	4.94	12.5	56.3	26.6	1
1.12	Near	20.3	4.88	2.4	94.7	27.7	[illegible]
1.13	Near	19.9	3.73	96.8	69.9	–	[illegible]

controlling the indoor air quality and temperature in summer, preventing overheating by adopting adequate ventilation strategy.

5.2.1. Door open

The doors bear poor correlation with indoor and outdoor temperature, as shown in Fig. 2. This suggests that an open door has little impact on thermal sensation and its use is not much influenced by indoor or outdoor temperatures. The frequency in Table 3 shows that the doors were open in 60–75% of the responses. The observations in figures and table indicate that there are factors other than thermal comfort which influence the opening and closing of the doors.

5.2.2. Window open

Open windows aid air movement and may help to cool the building and occupants in summer. Of all available controls, windows have the biggest effect on indoor climate. On an average, 62% of the total responses reported open windows, ranging from as high as 81% in building 2 (Oxford) to as low as 11% in building 14 (Aberdeen) (see Table 3). The use of windows varies from person to person and the seating position as indicated in Table 4. Obviously a person near the window will have the greater control.

The 'open window' is closely related with thermal sensation, indoor and outdoor temperatures as shown in Fig. 3. The proportion of windows open increases as the subjects feel hotter on the comfort vote from 1 (=much too cool) to 7 (=much too warm). Reasons given for closed windows are "others want them shut," "to prevent draught," "to keep the noise level low," or "interference with blind".

5.2.3. Cross ventilation (door–window open)

In warm and hot climate regions, the buildings are designed to provide cross ventilation. It seems to be less important in cold climatic regions. The climate of UK is

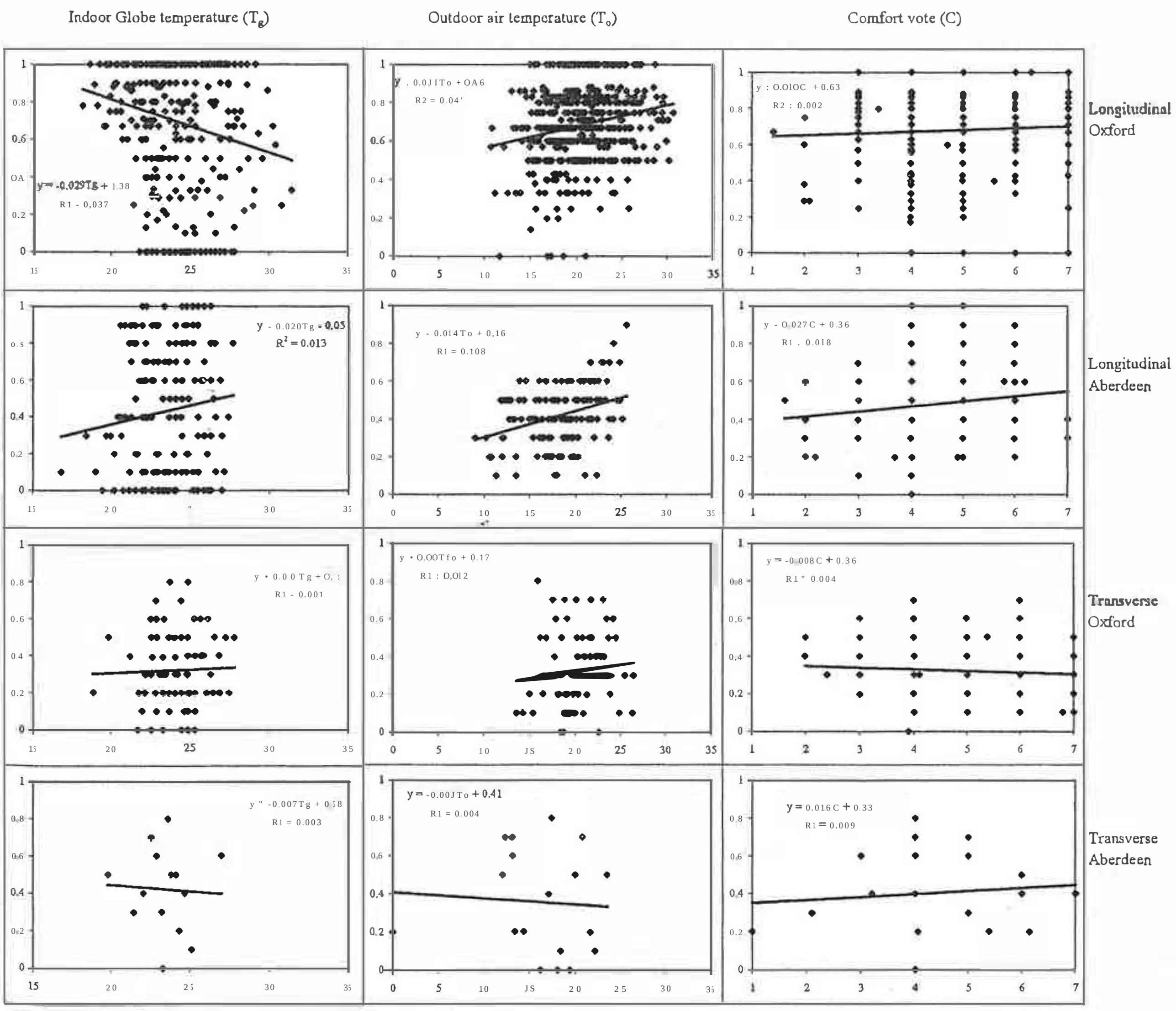

Fig. 2. Relationship of "open doors" with indoor and outdoor temperatures and thermal sensation.

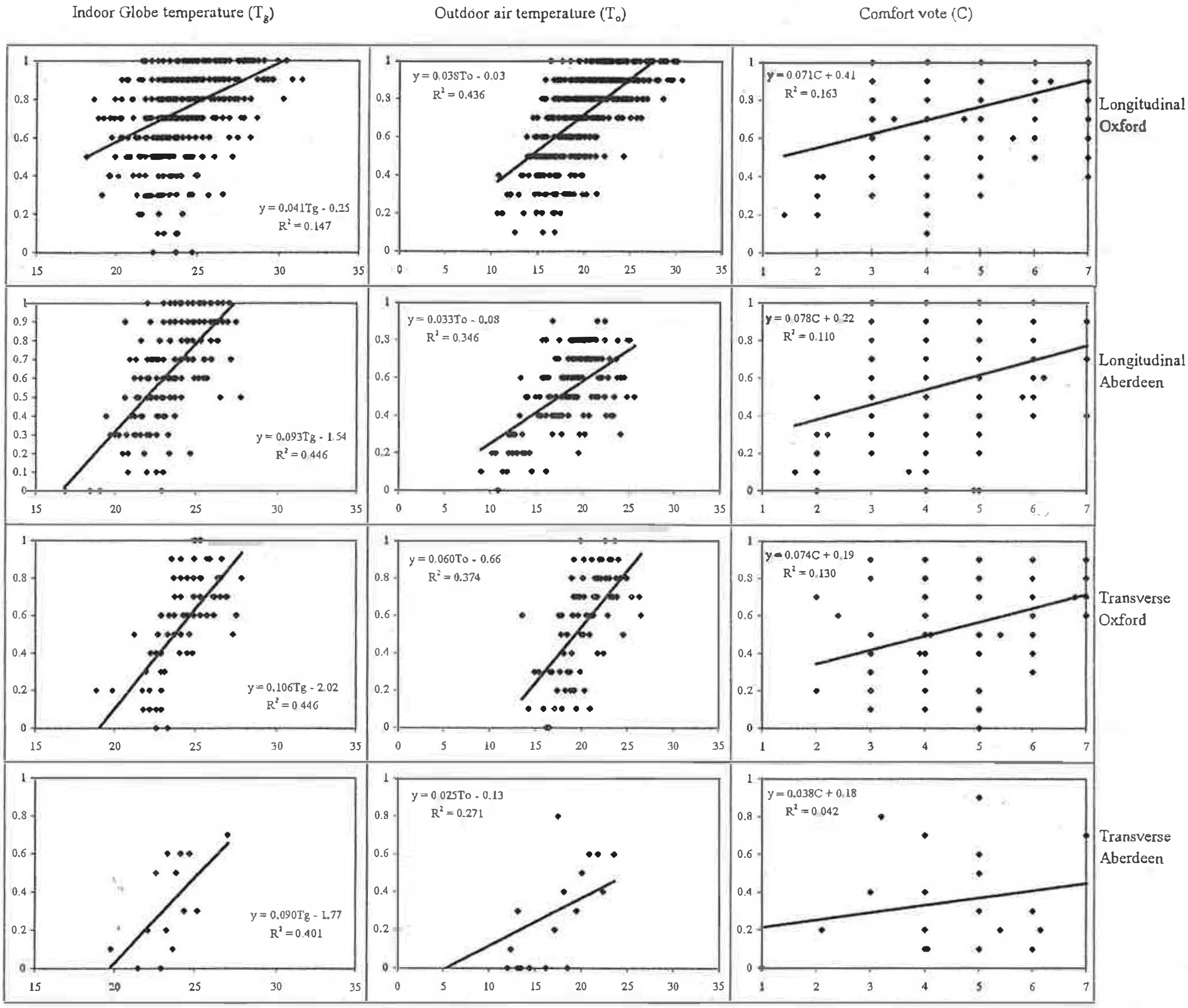

Fig. 3. Relationship of "open windows" with indoor and outdoor temperatures and thermal sensation.

regarded as cold. Despite this fact, in an earlier study, based on the data from one building, i.e. Building 1 [1], it was shown that cross ventilation (i.e. both door and window open) was effective in reducing the indoor temperatures. The temperature drops by about 1.5°C when both windows and doors are opened. However, this effect is less marked when data from all buildings are used (Fig. 4).

5.2.4. *Use of fans*

In naturally ventilated buildings, fans play a significant role in reducing the heat stress. Use of fans modifies the indoor climate by regulating and increasing air movement. Fig. 5 shows that the proportion using fans bear a strong correlation with indoor and outdoor temperatures and thermal sensation. The correlation coefficients are comparable to that for 'window open'. However, its use is relatively low (38% on the average, mostly below 30%), as shown in Table 3. Despite the increase in 'fan usage' with the increase in three parameters, the small proportion of people using fans suggests either that fans are not available or that the other means of ventilation are sufficient to achieve indoor thermal comfort.

5.2.5. *Heat gains*

Heat gains may be internal or external. Internal heat gain is due to the use of energy consuming equipment and occupancy. Among these artificial light is a significant as that can be avoided during the day time when the daylighting is enough. External gain is mainly the solar — direct or indirect. The controls used to limit the direct solar radiation are blinds or curtains.

5.2.6. *Use of blinds or curtains*

One function of blinds and curtains is to intercept the direct solar radiation entering the building in warm or hot weather. They are used by all subjects where appropriate

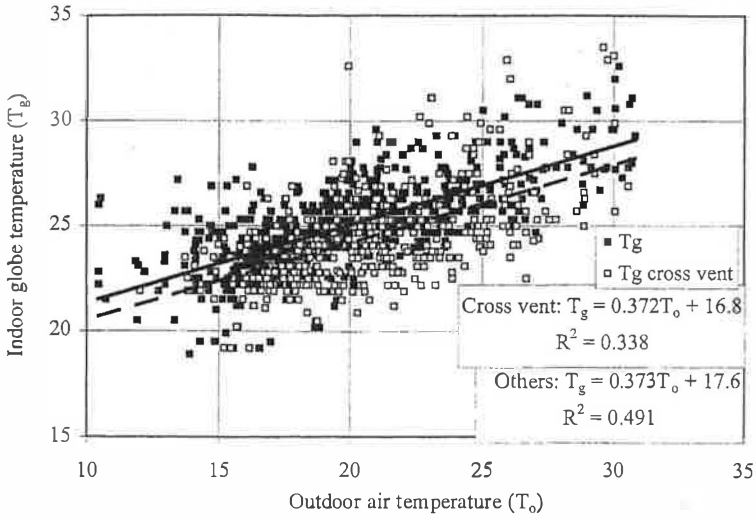

Fig. 4. Effect of cross ventilation on indoor climate.

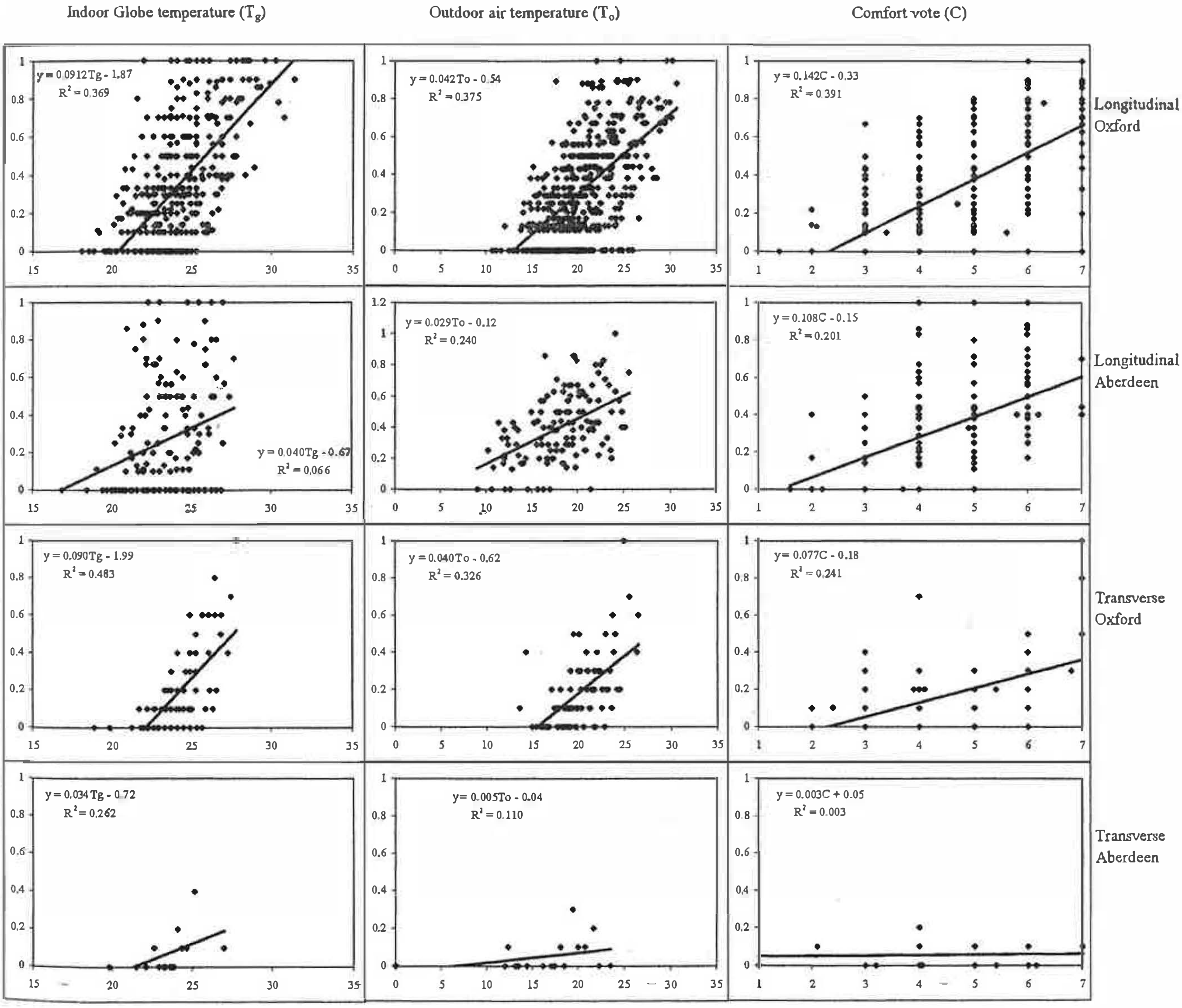

Fig. 5. Relationship of "running fans" with indoor and outdoor temperatures and thermal sensation.

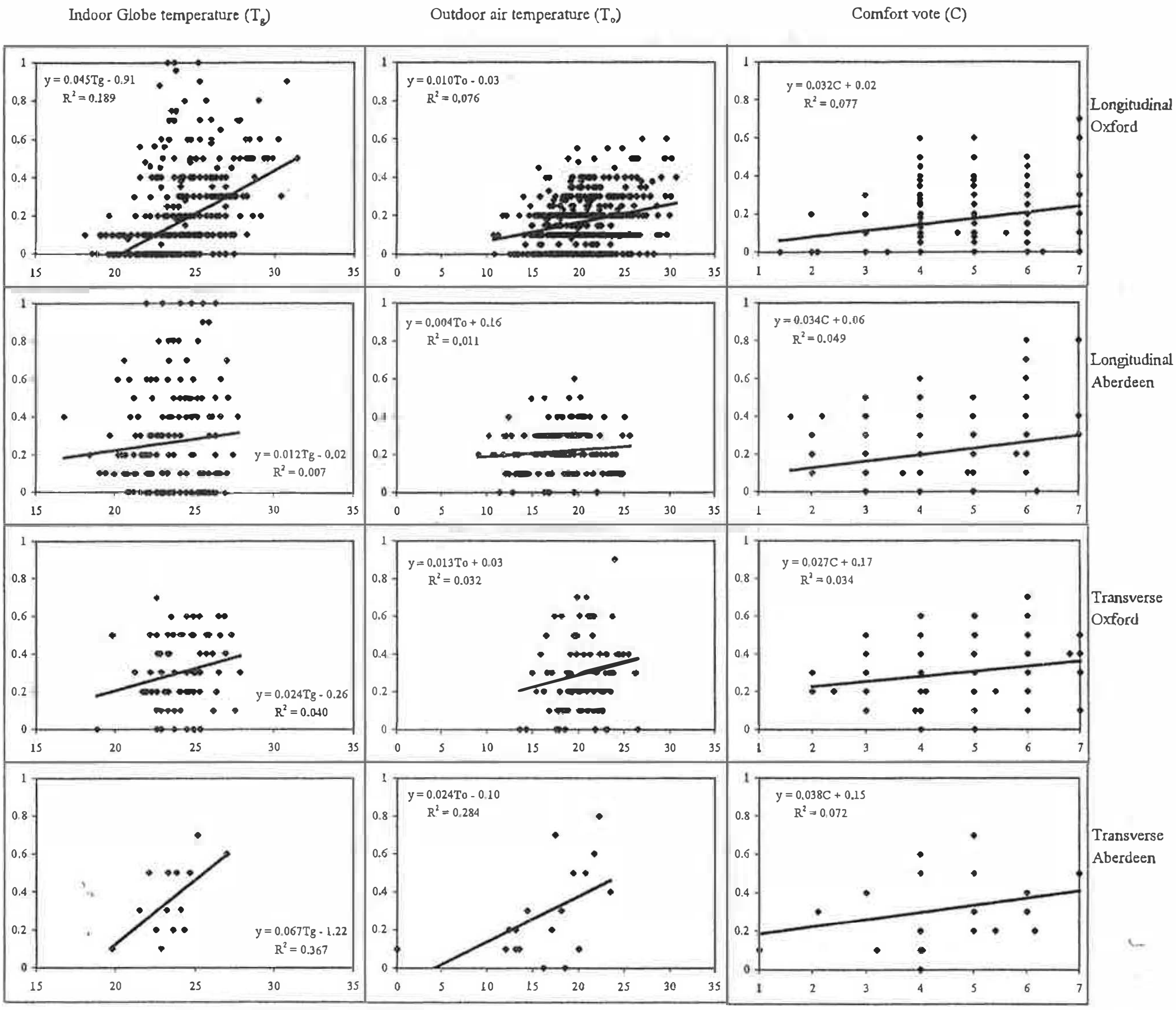

Fig. 6. Relationship of "blinds/curtains down" with indoor and outdoor temperatures and thermal sensation.

with "glare reduction on VDUs" and "reduction of direct sunlight" given as reasons. The use of curtain/blinds is usually <20%, being drawn in about 24% of responses overall (Table 3). The use of blinds/curtains varies from building to building and within a building from person to person with seating position (Table 4). People near to the window use blinds most extensively (76.2%). A person away from the window records the least use of windows (8.1%). The 'blind/curtain usage' increases with the increase in indoor and outdoor temperatures and thermal sensation (Fig. 6), but the rate of change is small compared to windows and fans probably because the reason for using blinds is to avoid glare rather than heat.

5.2.7. Use of artificial light

In UK climatic conditions, lights are more extensively used in winter than in summer. Regression analysis of light with thermal sensation, indoor and outdoor temperatures resulted in a very low correlation. However, despite a lc correlation, Fig. 7 suggests that on sunny days in summ people tend not to switch on the lights. In open plan offic individual users have less control over general lights. The fore, despite adequate daylighting the lights have been fou on in many places. Switching on the light in early morni often means that it stays on throughout the day.

6. Discussion

The results presented suggest that windows are us extensively by building occupants. At indoor temperatu in excess of 20°C the number of subjects reporting t opening of windows rises steeply with indoor temperat and approaches 100% at temperatures above about 27 (Fig. 3). Outdoor temperature is also an indicator of t likelihood that windows are open. Few are open when t

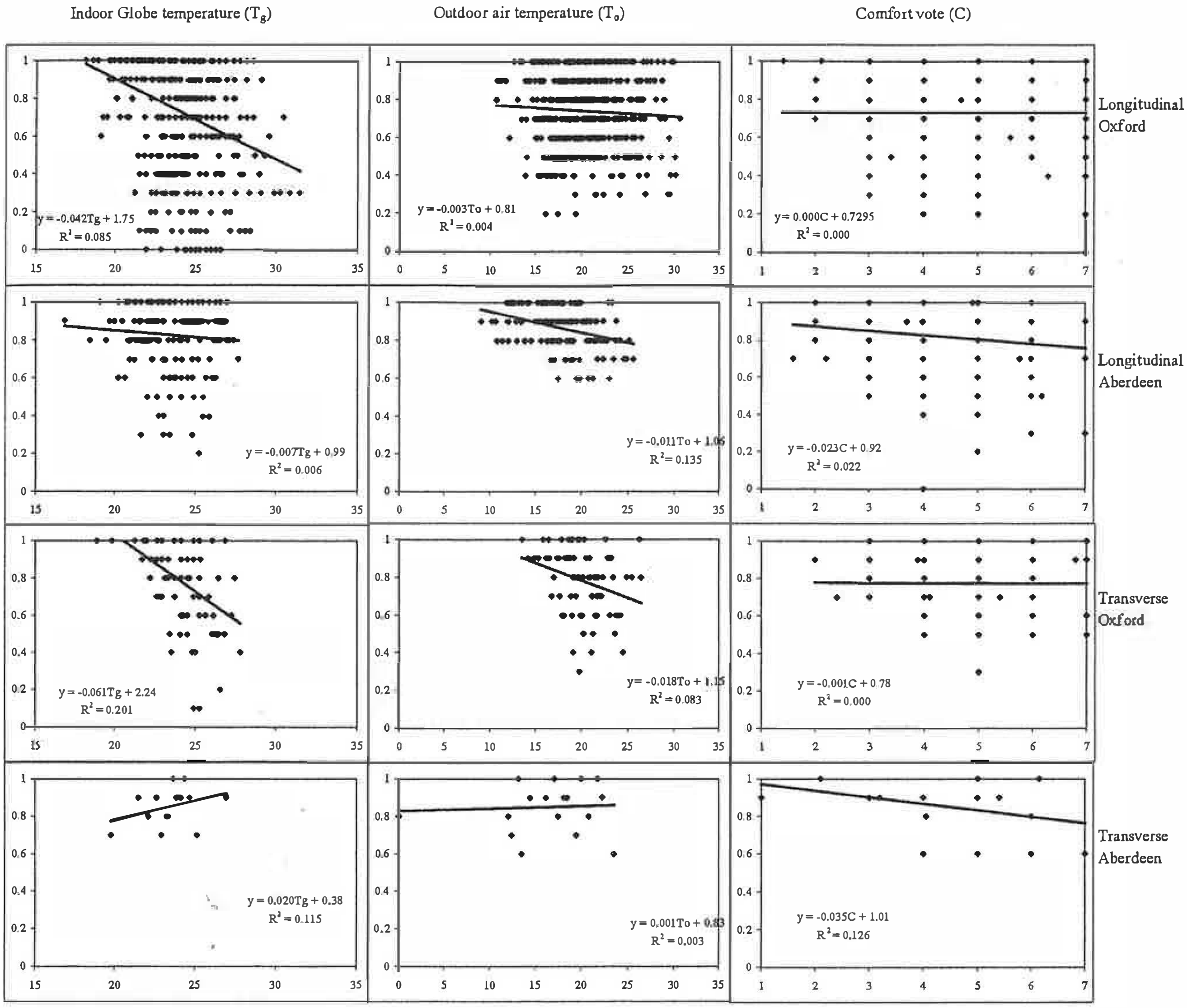

Fig. 7. Relationship of "lights on" with indoor and outdoor temperatures and thermal sensation.

outdoor temperature is below 15°C, but when the temperature outdoors exceeds about 25°C most windows are open. The relationship is not close and many other factors are clearly playing a part in the decision to have the window open, but the overall effect is robust.

The other clear relationship is between temperature and the use of fans. Here again the indoor temperature of 20°C and an outdoor temperature of 15°C are the thresholds at which fans begin to be used. The use of fans rises to about 50% when the indoor temperature rises to the upper twenties of degree Celsius. The relationship with comfort vote suggests that the use of fans is strongly related to heat.

It is interesting to compare the findings of this survey with those from a similar transverse survey conducted in Pakistan [6]. The use of windows and the use of fans are both related to indoor and outdoor temperature. Though the use of windows only rises to a maximum of about 50%, the threshold temperatures of 20°C indoors and 15°C outdoors seem to be the same and the same applies to the use of fans. The use of fans (which are almost universal in Pakistani workplaces) rises to 100% at high indoor temperatures but is about comparable to that in Britain (i.e. 50%) in the upper twenties of degree Celsius.

Thus, these relationships which are valid in summer conditions in Northern Europe were found to apply throughout the different climatic zones of Pakistan.

7. Conclusions

Availability of controls and their appropriate use is key to better performance of the building and for improving occupant satisfaction. The analysis of the data collected during the present study shows that the use of various controls plays a significant role in modifying indoor thermal conditions.

Opening of windows and drawing of blinds or curtains are the most extensively used. The proportion of windows open and blinds/curtains drawn increased with an increase in indoor or outdoor instantaneous temperatures. The study shows that blinds/curtains are fully drawn or half-drawn in about 24% of the responses and 'window open' for 62% of the responses. In two separate thermal comfort studies, [3,7] found the use of control — opening windows or deploying blinds — in 31.6 and 39.9% of cases, respectively. The use of fans also showed a similar trend as for windows and blinds. The proportion of subjects using fans is relatively high in buildings with a lower proportion of open windows.

The incidence of discomfort is strongly correlated with the use of windows and fans suggesting that these controls are used in response to discomfort, in accordance with adaptive theory. Allowing cross ventilation also helps to lower the indoor temperature. Occupants who have greater access to controls (e.g. those close to a window) report less discomfort than those who have less access (e.g. away from the window). There are, therefore, significant opportunities for adaptation by simply operating local controls: windows, doors and blinds/curtains. In buildings, where more control is needed, fans can be used to increase air movement.

The data presented in this study suggest that computer simulations of naturally ventilated buildings should assume an increasing rate of ventilation due to open windows at indoor temperatures above 20°C or outdoor temperatures exceeding 15°C.

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