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THE PASSIVE SOLAR HEATED SCHOOL IN WALLASEY. VII

WINDOW OPENING BEHAVIOUR AND THE MICROCLIMATE OF A CLASSROOM

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SUMMARY

Previous work on factors which influence the opening or closing of windows suggests that at low ambient temperatures movement might be associated with odour levels, at intermediate temperatures, with ambient humidity and at higher ambient temperatures with the need to cool buildings.

The data on window position, together with other physical measures during the period of observation in the Wallasey School, has been examined to see what quantity is most closely associated with window position. It appears that in the classroom the number of open windows depends mainly upon air temperature, but it also depends markedly on time of day.

KEY WORDS Solar heating Passive solar design Window opening behaviour

1. INTRODUCTION

What causes people to open—or close—windows? The question of how many windows may be open in particular circumstances has been the subject of enquiry at least since the work of Dick and Thomas (1951), who found that the number of windows open varied linearly with the mean outdoor temperature. Brundrett (1977) has more recently reported a study on window opening habits in a total of 123 houses on modern estates and reports that the number of open windows is strongly linked to external moisture levels in winter and to mean temperature in summer. He mentions three possible domains of temperature: below an ambient temperature of 12°C window opening habits are related to odour levels and the need for fresh air; between 12°C and 20°C they are related to moisture levels, and above 20°C to the need for cooling.

The observational study in the Wallasey School provided a quantity of information on the state of the windows at all times of the day and night, together of course with various measures of temperature. As far as user behaviour is concerned, only that part of the data is of interest which was generated while the children might be present—interpreted here as between 08.40 and 16.00 h. This information is of some importance, however, for two reasons. First the data refer to conditions actually within the occupied space. One must suppose that the action the occupants take in opening or closing windows is more related to indoor conditions than outdoor conditions, whether they be ambient temperatures or humidity. Secondly, the architect intended that the windows should provide a ready means of cooling the building and it is of interest to see how the occupants made use of this facility, and how effective it was.

This article reports the probability that at some value of indoor temperature, one, two or no windows were open. It goes on to examine what physical quantity seems most closely associated with the action of opening or closing the windows.

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2. DATA PREPARATION

The computer outputs of the raw data for the period 1 January 1969 to 23 July 1970 were scanned visually to identify occasions when one or two of the classroom windows changed position. The computer records indicated '0' when both windows were closed, '1' if one or other had been opened, but without regard to which, and '2' if both were opened. The record indicated only whether a window was firmly closed and secured by the clasp, or whether it was not: the extent of opening was not indicated—nor of course the extent of any air movement through the gap. The authors' experience over many years suggests that once open, a gap of some 10 cm is commonly to be found, but the windows can be opened sufficiently to permit a person to climb from inside to outside.

In the first part of the study, the mean room air temperature was recorded at 08.40, 09.00, 09.20, . . . , 16.00 together with a note of whether 0, 1 or 2 windows were opened. According to the timetable for 1968–1969, the first class of the day started at 09.25. Children would by then have attended morning assembly and those who entered the classroom beforehand would have been able to open a window at 09.00. Teachers sometimes arrive much in advance of the children. Thus the 08.40 scan was selected as the first opportunity of the day for evidence of occupation to show itself. Classes formally ended at 15.45, but some activity continues for a while, and the 16.00 scan was chosen as the last effective scan during occupation. Only days of normal occupation were included; weekends, half terms and holidays were excluded. A quantity of data was either missing or too corrupt to allow reconstruction.

To provide data indicating the conditions before a window was opened or closed, the records were searched for consecutive scans which indicated a change in 'window open'. If for example on the 10.40 data scan registered '0' and the 11.00 scan registered '1', certain quantities in the 10.40 scan were recorded, together with 0 and 1 in that order. The 10.40 scan provided the best available information on the physical environment that led to a change in window position. The quantities recorded were:

(1) date
(2) time of scan
(3) globe temperature
(4) floor surface temperature
(5) ceiling surface temperature
(6) wet bulb temperature
(7) contemporary window state
(8) later window state
(9) mean surface–air temperature difference
(10) mean air temperature
(11) indoor air–ambient air difference
(12) intensity of radiation incident on the solar wall
(13) ambient air temperature.
(Item 11 was redundant).

3. THE STATE OF WINDOWS DURING OCCUPATION

The raw data on window opening provided a total of 5141 occasions when the state of the windows during occupation was known. Their distribution over month and room air temperature is shown in Table I.

Table I shows a spread of mainly low temperatures during winter and high temperatures during summer. This was noted in paper IV of this series (Davies, 1986). Certain features become clearer when these results are processed.

Windows may be found open at any time during occupation, but the probability of finding one or two open increases with temperature. This is shown in Figure 1(a) where the frequencies of occurrence of 0, 1 or 2 opened windows have been normalized. (Thus at 16·5°C, the frequencies of 0, 1 and 2 open windows are 168, 24 and 16, or probabilities of 0·808, 0·115 and 0·077.) The frequencies outside the range 16·0 to 24·0 are too small to allow reliable computation of probabilities.

Table I. Distribution of the frequency of the state of the windows in relation to month and to indoor air temperature

Columns: indoor air temperature, °C. Second column: number of windows open.

	Number of windows open	14		15		16		17		18		19		20		21		22		23		24		25		26		27		28
Jan	2							2	5	1																				
	1					1	3			2	1	1																		
	0			1	2	5	14	22	18	9	12	4		1																
Feb	2					2	9	4	1	1	1	8	1																	
	1			1			7	1	1																					
	0		5	4	12	26	25	22	20	8	7	2	2	2																
Mar	2						1	3	6	4	2	5	7	8	2															
	1		3	1	2	4	3	9	15	15	12	8	4	3	2	1														
	0		1	15	18	54	47	49	53	39	27	21	12	6	4	2	2													
Apr	2					1	1	2	3	6	17	8	2	4	2	4	2													
	1						4	2	3	6	7	7	9	5	6	6	7													
	0						1	8	4	7	4	18	7	10	5	2		2												
May	2						1	4	7	4	3	4	6	6	8	5	2	2												
	1						3	6	6	7	4	11	11	9	8	1	1	2												
	0						3	5	8	8	16	19	12	6	6	5		1												
Jun	2								1	4	2	4	3	2	8	16	18	17	21	20	14	12	4	1	3	3		1		
	1									1	5	10	12	9	24	20	20	6	11	2	3	1			1					
	0									10	7	3	4	14	13	20	17	15	1	2	1	1	1							
July	2											1	3	4	10	16	18	10	15	12	13	17	15	12	5	3	2	1	4	
	1											1	2	3	9	13	5	5	11	8	8	4	5	8	1	1				
	0												3	6	16	8	4	7	12	12	7	1	3	3	1	2				
Sep	2					1			6	5			6	14	17	10	13	18	17	6	4	1								
	1									1		2	9	16	30	36	19	19	11	4	1	2	2	2	1					
	0												2	9	17	8	4	9	1											
Oct	2					2	3	1		5	14	16	9	22	10	6	5	6	5	4	5		2	3	2	1				
	1								1	7	11	17	30	37	15	13	13	12	11	10.	4	6		2						
	0									1	12	25	27	27	30	34	15	2	1	1										
Nov	2								1		1																			
	1						2	10	10	6	2	1		6	2	1	2													
	0				1	3	1	17	47	18	13	12	5	8	4	7	5	4												
Dec	2									3	1	2	3	2																
	1							4	9	29	16	5	3	1	1	1	1	1												
	0				2	19	23	28	31	18	9	9	4	3				1												
Jan	2								1	1			2																	
	1			2	9	2	1	1	10	5	4	3	2	3	1	1														
	0		7	14	35	57	49	54	36	19	14	4	7	3	4	1		1												
Feb	2					1	1	1		3	4		1	3	4	2	4													
	1							7	6	3	2	2	3	2	1	9	1	4												
	0	1			3	3	5	12	18	24	12	21	17	11	11	4	2		2		1									
Mar	2							1	3	6	2		7	4	5	4	2		1	1										
	1						1				3	9	2	12	8	4.	1	1												
	0							1	2	17	31	35	36	32	27	25	19	6	14	2	2									
Apr	2											2	4	10	6	3	10	9	4											
	1							1		3	3	8	22	13	12	7	11	7	4	4										
	0											2	20	30	35	27	18	11	2	3	2	1	2							
May	2									5	5	8	4	14	20	18	21	10	19	12	8	1								
	4												4	10	21	17	19	10	4		1									
	0									3	4	1	10	19	20	20	18	10	6	3	2	4	3							
Jun	2														1	2	8	11	7	14	18	15	7	10	3	7				
	1															3	5	3	6	6	4	1	1	1	4					
	0														2	5	3	6	6	6	5	4	2	1	2					
July	2											2	10	8	10	12	15	9	6		1			1	1	4	2			
	1										1	8	12	18	20	18	12	18	12	4	1	1		1						
	0											2	1	6	20	37	28	17	10	5		1	1							
						7	16	18	34	48	52	60	68	101	103	98	118	92	95	69	63	46	28	27	14	18	4	2	4	
			3	4	11	7	24	41	61	85	71	93	125	147	160	151	111	88	70	38	22	15	8	14	7	1				
		1	13	34	73	167	168	218	237	181	171	186	169	193	214	205	135	92	55	35	20	12	12	4	3	2				

indoor air temperature, °C

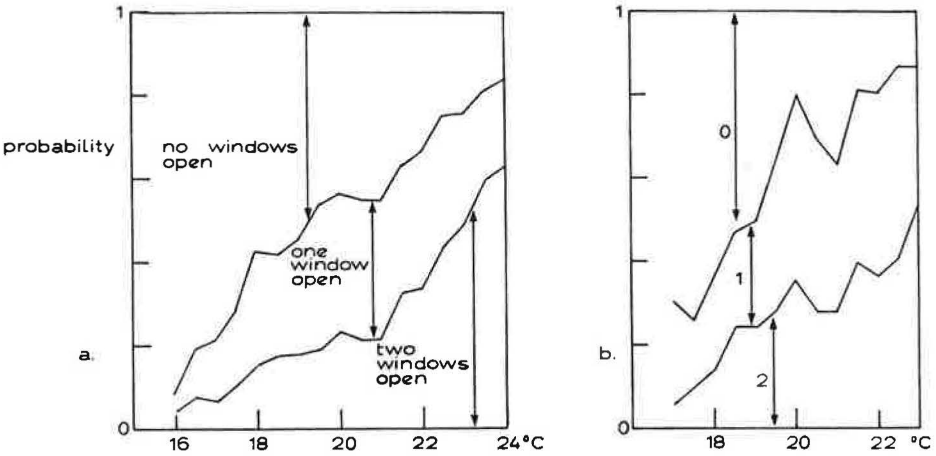

Figure 1. Probability of finding no windows, one window or two windows open as a function of room air temperature noted at the same time. (a) includes all times of day. (b) includes only those scans during mid-afternoon when the overall probability of finding one (or two) windows was varying little. It therefore shows the probability as a function of temperature alone, without much time of day effect

Figure 1(a) provides strong quantitative confirmation of the marked increase in incidence of window opening as indoor temperature increases. However p_w, the probability of finding one window open, increases with time of day (until-afternoon). Further, room temperature T_{ai} also increases with time of day. It could be that if time of day were held constant, p_w would not show a variation with T_{ai}. To examine this possibility the variation of p_w with T_{ai} was found for a narrow range of time of day. The range consisted in the five scans between 14.00 and 15.20, during which the number of windows opened varied little with time of day. The variation found is illustrated in Figure 1(b). With only 1131 observations the statistical fluctuations have a bigger fractional effect, and results have to be confined to a smaller range of temperatures (17 to 23°C). Figure 1(b) shows a marked increase in p_w with air temperature, indeed a rather faster increase than does Figure 1(a).

Although windows are more likely to be opened at higher temperatures, the mean air temperature during any one month does not vary much with the state of the windows. This is seen in Table II. Over the period as a whole, air temperature and windows opened certainly covary—18·9, 20·2 and 21·2°C for 0, 1 or 2 windows opened, but individual months may show T_{ai} either increasing or decreasing with windows opened.

One intended effect, of course, of opening a window is to lower air temperature and this to a large extent explains the comparative within-month lack of variation of temperature with window opening. To see quantitatively what the overall cooling change amounted to, the daily sequences of windows open/temperature were examined and those occasions noted when a sequence of 0, 0 and 0 windows opened was followed by a sequence of 1, 1, 1 windows opened, i.e. windows were in the closed state for an hour, so that the ongoing temperature history could be established, and then, following the opening of one window, the subsequent temperature history could be followed. A total of 63 such sequences was found. The mean temperatures are shown in Figure 2. The temperature trend throughout the day is upward, until near close of school. The mean temperature during the period when no windows were opened shows this feature. Had no window been opened it would have continued upward, as suggested by the dotted line. However, the effect of opening a window is to cause an immediate (i.e. between consecutive scans) drop of 0·70 K, followed by a slow fall, instead of a comparatively rapid rise. The two-open-windows condition would show a sharper effect. The windows are thus very successful in restraining temperature rise.

An analysis was made too of the number of windows to be found open during the course of the day (see Figure 3). Windows were normally kept closed during the night though occasions were noted when a window remained open all night. (On one such occasion the temperature fell to nearly 10°C by the following morning.) Generally speaking windows were observed to be closed at 08.40 and were often opened during the first hour of occupation. Thereafter, the number opened increased slowly until 14.40 after which the occupants started to

Table II. Monthly mean air temperature and number of opened windows

Month		No window open		One window open		Two windows open	
		n	$\bar{T}_{ai}$	n	$\bar{T}_{ai}$	n	T_{ai}
Jan.	104	88	17·3	8	17·4	8	17·4
Feb.	172	135	16·7	10	16·5	27	17·6
Mar.	470	350	17·3	82	17·8	38	18·8
Apr.	179	71	18·9	56	19·1	52	18·9
May	210	89	18·9	69	19·0	52	19·3
Jun.	388	109	20·6	125	20·8	154	22·2
Jul.	330	85	22·1	84	22·4	161	23·0
Sep.	323	50	20·8	155	21·2	118	21·0
Oct.	485	175	20·1	189	20·6	121	20·3
Nov.	189	145	18·4	42	18·3	2	18·0
Dec.	229	147	17·4	71	18·3	11	19·0
Jan.	353	305	16·8	44	17·5	4	18·6
Feb.	219	155	18·6	40	19·3	24	19·5
Mar.	326	249	19·9	41	19·8	36	19·6
Apr.	296	153	20·8	95	20·4	48	20·9
May	354	123	21·0	86	21·0	145	21·2
Jun.	179	42	22·7	34	22·9	103	23·5
Jul.	335	128	21·3	126	21·0	81	21·4
All months	5141	2599	18·9	1357	20·2	1185	21·2

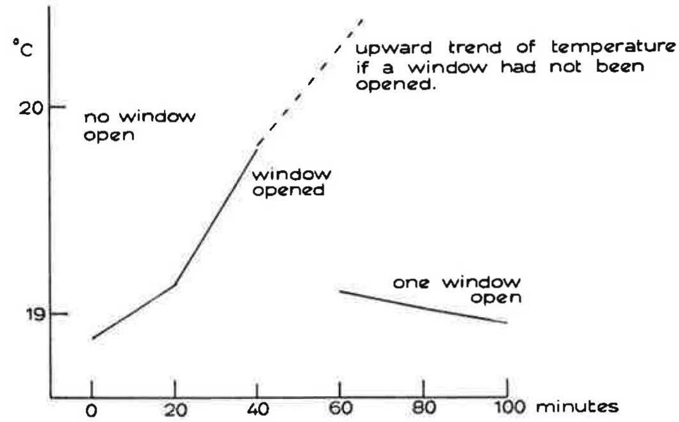

Figure 2. The mean temperature change during the period before and after a window is opened

close them again. Windows often remained open after 16.00. For some years a notice signed by the headmaster was attached to the staff notice-board instructing staff to close windows by 4 p.m. but the data showed that in fact closure often came much later. It was probably effected by the caretaker or the cleaners.

Figures 4(a) and 4(b) show the probability of windows being opened against time of day for low, medium and high temperatures. (These ranges were chosen so as to contain around one third each of the total number of observations.)

Although the state of the windows was clearly dominated by air temperature, an analysis was performed to see what dependence there might be on relative humidity. Humidity was computed from simultaneous indoor dry and wet bulb temperature observations which were available on a total of 4688 occasions. Figure 5 shows the probabilities of finding 0, 1 or 2 windows open as a function of relative humidity. (The values illustrated are based on more than 50 occasions each.) Using data for the complete period of occupation the probability of

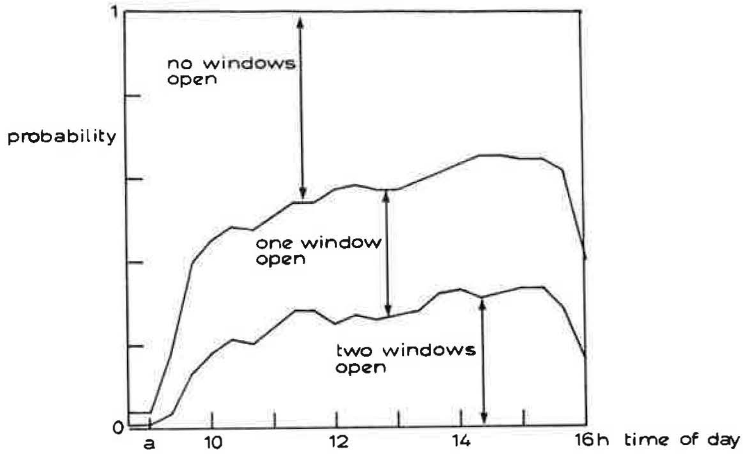

Figure 3. The probability of finding 0, 1 or 2 windows open as a function of time of day; all data are included

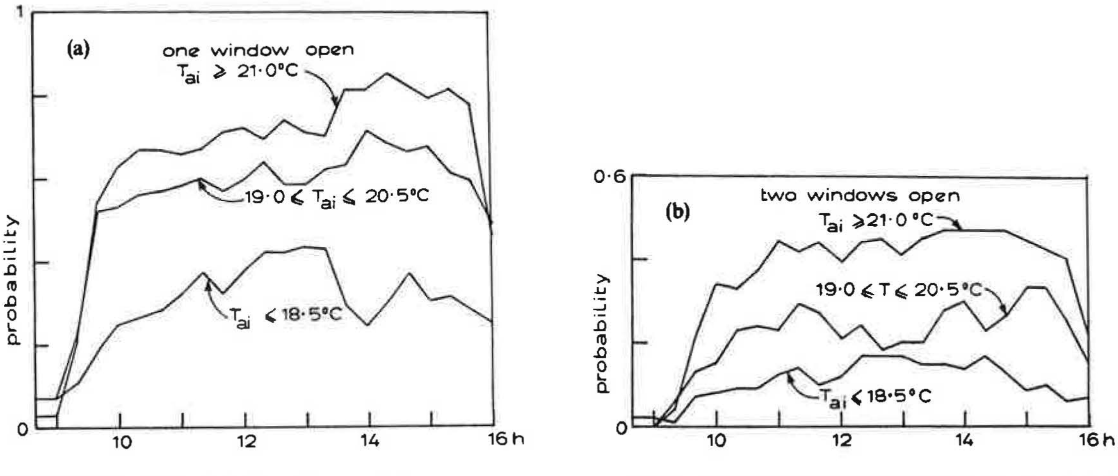

Figure 4. The probability of finding (a) one window or (b) two windows open as a function of time of day, with due regard to the air temperature, T_{ai}

finding two windows open does not vary much. The probability for one window indicates a marked and complicated form of variation. With several hundred occasions for most of the points each taken at intervals of 5 per cent relative humidity, this variation would appear to be statistically reliable. Figure 5(a) could be taken to mean that the occupants have some slight perception of relative humidity, in addition to temperature, which leads them to open or close a window. There may be however a purely physical explanation: wet bulb temperature covaries with dry bulb temperature, outdoor humidity and the number of children present. Dry bulb temperature depends on similar variables. The probability of opening a window presumably depends to some extent on the numbers of children present. The development of a model including these considerations however lies outside the scope of this report. It may be remarked that Figure 5(b), based on the five afternoon scans when the time of day effect is not present, shows a relation not very different from that of the full data set.

4. PHYSICAL MEASURES AND WINDOW MOVEMENT

Although it is broadly accepted that people open windows in hot weather it is not obvious to what measure of temperature people are most sensitive as far as their opening of windows goes. Since the Wallasey data

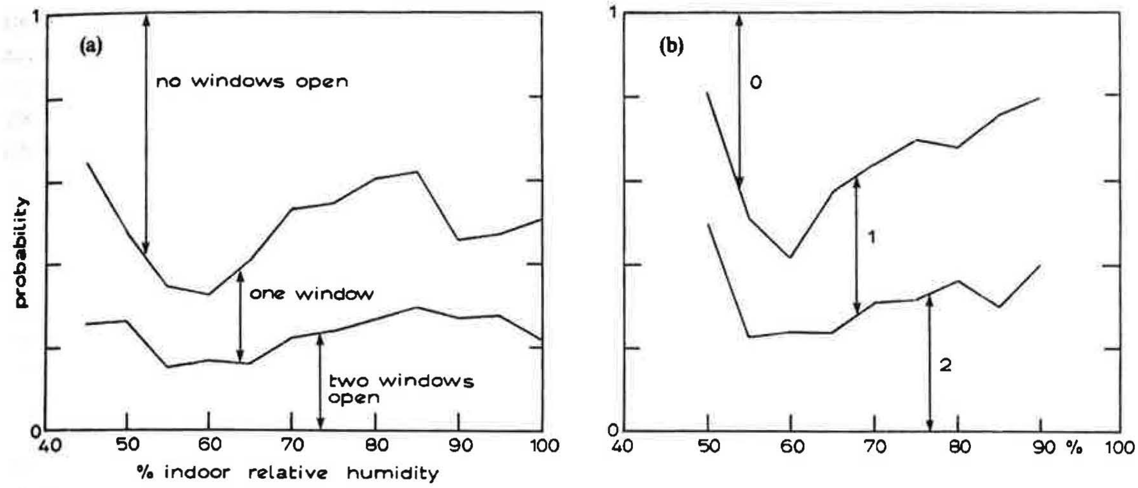

Figure 5(a). Probability of finding no windows, one window or two windows open as a function of relative humidity, including data from all times of occupation. (b) As (a) but including only the five mid-afternoon scans when the probability of finding the windows open or closed varied little

provided various measures of temperature, the data set offered an opportunity to examine this matter, and also to see whether humidity or solar radiation had any influence in this particular environment. Accordingly, other measures as noted in section 2 were recorded.

Consider the possible action of occupants in a situation of gradually rising temperature. The probability of opening a window increases and this can be represented by the right-hand curve in Figure 6(a). Since people exhibit a certain time lag in responding to the environment, we would suppose that as ambient temperature fell again, the probability of a window being open would be somewhat higher at a given temperature than during the period of rising temperatures. The corresponding probability would be described by the left-hand curve in Figure 6(a). (The separation between the curves might be expected to depend on the rate of temperature change: if temperature changed very slowly, the curves might be expected to coincide.)

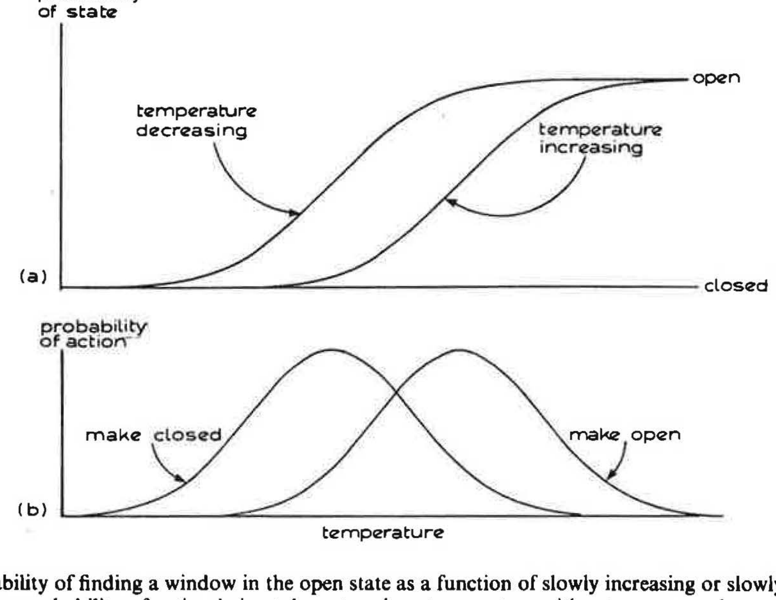

Figure 6(a). The probability of finding a window in the open state as a function of slowly increasing or slowly decreasing temperature. (b) The probability of action being taken at a given temperature, either to open or close a window

The gradients of the curves in Figure 6(a) represent the probability of 'making open' (while temperature increases) or 'making closed' (while it decreases) and these probabilities are shown in the bell shaped curves of Figure 6(b).

If an environmental variable has any influence on window movement, one may suppose that a measure of its influence is the distinctness of the two distributions of Figure 6(b). A measure of distinctness between the groups is

$$C = \frac{\text{separation of the means}}{(\text{pooled variance})^{1/2}}$$

and the significance of C is given by Student's t:

$$t = C\left(\frac{1}{n_1} + \frac{1}{n_2}\right)^{-1/2}$$

where n_1 and n_2 are the numbers of occurrences of 'making open' and 'making closed'.

In order to arrive operationally at Figure 6(a), we need a comparatively large quantity of data on the chosen measure. With air temperature as the chosen variable, this was presented in the last section. It is however laborious. To arrive operationally at Figure 6(b) on the other hand, we have simply to note the values of the environmental variables that seem of interest immediately prior to a window movement. This is much less laborious.

In fact it provided a total of 513 occasions, 319 associated with opening and 193 associated with closing. An initial look at the data however indicated that a number of the window movements took place not long after school started. (This was noted above.) Since this seemed to be a time of day action not very dependent on the measurable physical state of the classroom it seemed appropriate to exclude such movements, and accordingly a subset of events on and after the 10.20 scan was selected for further analysis. This resulted in 163 openings and 154 closings. The discrimination values C of the various variables are noted in Table III. (Relative humidity is found from variables 4 and 6.)

Table III. Discriminant power C_j of individual measures to distinguish between opening and closing of windows. Period of analysis: 10.20 to 16.00 h.

	All year	Winter	Spring	Summer
n (opening)	163	58	41	53
n (closing)	154	65	31	49
C_j to reach 5 per cent significance level	0·22	0·36	0·48	0·40
Globe temperature	0·35**	0·32	0·58*	0·22
Floor temperature	0·12	−0·01	0·32	0·08
Ceiling temperature	0·05	−0·05	0·10	−0·07
Wet bulb	0·37**	0·33	0·70*	0·16
Surface − indoor air	−0·43**	−0·29	−1·15**	−0·68*
Indoor air	0·47**	0·46*	0·71*	0·34
Indoor − ambient	0·11	0·25	0·18	0·30
Incident solar radiation	0·30**	0·40*	0·16	0·45*
Ambient air	0·08	0·01	0·14	−0·01
Relative humidity	0·06	−0·08	0·46	−0·27

Winter = November, December, January, February, March.
Spring = April, May.
Summer = June, July, September.
October is included in the all year data, but not in the seasonal data.
* denotes value significant at the 5 per cent level of probability.
** denotes value significant at the 1 per cent level of probability.
(Other values are statistically insignificant).

Before commenting on the all-year values, it is convenient to subdivide the data into seasons. To do this, the mean window position was plotted against mean monthly temperature for the 18 months of available data (see Figure 7). This indicated clearly that the two Januarys, Februarys and Marchs, together with November and December were to be classified as winter months. Equally Junes and July and September 1969 were summer months. Both Aprils and May 1969 lay in an intermediate position and could be treated as spring. May and July 1970 do not so readily fall into spring and summer classifications, respectively, but were nevertheless so classified. Since the general seasonal quality of October differs substantially from spring, it was not included with April and May, and was simply omitted from the subdivided data.

A value of t of about 2 (with sample sizes of this order) indicates that the observed value of C_j might occur by chance on one occasion in about 20, $p < 0{\cdot}05$, if a parent population were sampled in which no discrimination by variable j were really present. This level of significance is taken to be 'just significant'. (If t is about 2·7, $p < 0{\cdot}01$, and the value is taken to be 'significant'.) The corresponding values for C_j for the sample size are noted in Table III. Any value of C_j less than about 0·22 in the 'all year' data is taken to be 'not significant'.

Inspection of Table III indicates that some of the measures provided non-significant discrimination: floor and ceiling temperature, the indoor–ambient difference, ambient temperature itself, and relative humidity. Some of the C_j changed signs across season.

Globe temperature appears to behave like air temperature but is weaker than it. Wet bulb covaries with indoor air temperature and appears to serve no useful purpose. This leaves the surface–air difference, indoor air and solar radiation as possible indicators of the act of opening or closing windows.

Indoor air is most straightforward. Since C (indoor air) is positive, it indicates that people open windows at a higher temperature on average than that at which they close them. The values for the all year data are 20·56°C as the mean temperature of opening and 19·65°C as the mean closing temperature. C (indoor air) is significant for the all year data and the winter and spring samples, but it does not reach significance in summer. This may be due to the fact that in summer windows are open a large proportion of the time. If the air temperature is sufficiently high the windows are already open most of the time, so the relationship between T_{ai} and window opening is not manifest: this does not of course imply that T_{ai} is not important.

The data on air temperature thus confirm the hysteresis model discussed earlier.

It may be that people really do open windows more readily in sunny conditions. The mean incident intensities on opening and closing (all year data, on and after 10.20) are 303 and 242 W/m^2, respectively. The result is as one might expect. However, solar radiation decreases towards the end of the school day; windows are closed toward the end of the school day. The observed difference between opening and closing intensities is certainly due in part to a time of day effect; it is not wholly an expression of environmental behaviour.

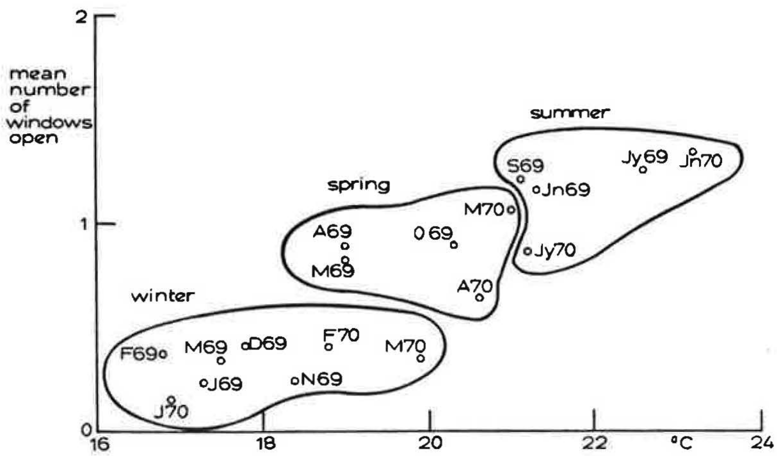

Figure 7. Mean monthly number of windows opened during occupied hours as a function of mean monthly temperature. The Figure shows the groupings used to examine whether different physical factors might tend to initiate window movement at different times of year

Finally the difference between surface and air temperature, T_{sa} appears to serve as an initiator for effecting window movement; it is significant except during the winter months. $C(T_{sa})$ is always negative: the air is nearly always warmer than the surfaces; air is 'much' warmer than the surface at times of opening and only a little warmer on closing (see Table IV).

There does not seem to be any physiological mechanism to enable people to sense air and radiant temperature separately, or the difference between them. The difference appears as an 'initiator' because of an artefact. The observed result may be explained by the following sequence. The environment during occupation is predominantly a warm-air–cool-wall environment; T_{sa} is negative and relatively large in magnitude; when a window is opened, it admits cool air, which reduces the room air temperature somewhat with little change in surface temperature. When in due course the window is closed again the air will be a little warmer or cooler than the surfaces. The air then starts to warm relative to the surfaces and during this phase, a scan records temperatures again, from which a small negative value of T_{sa} is usually found. Hence the result.

Thus air temperature, not surprisingly, emerges as the best physical indicator of the probability of opening or closing a window.

One may however enquire further whether any other measure could usefully be combined with air temperature to provide a better indicator than air temperature alone. Do people respond to a combination of air temperature and, say, solar radiation or relative humidity in some way?

This question can be tackled using discriminant function analysis, first proposed by Fisher (1936), and discussed by one of us (Davies, 1970). We have to know the C_j for each proposed variable together with the correlation coefficient r between them. r is based on the pooled covariance of variables 1 and 2.

The best combination of variables can be shown to yield a separation D between the variables given by

$$D^2 = (C_1^2 + C_2^2 - 2rC_1C_2)/(1-r^2)$$

(D^2 is similar in form to the multiple regression correlation coefficient, R^2. In Appendix II to paper VI of this series (Davies and Davies, 1987) there is a discussion regarding whether $R_{1,23}^2$ which depends on the three correlation coefficients r_{12}, r_{13} and r_{23}, is likely to be larger than r_{12}. Similar considerations apply here if C_1 replaces r_{12}, C_2 replaces r_{13} and r replaces r_{23}.)

Three or more variables can be similarly combined if the intercorrelations between variables are known. D_2, based on two variables, must significantly exceed the larger C_j variable which it includes. D_{t+u} based on $(t+u)$ variables must significantly exceed D_t, etc. The significance of the improvement in discrimination by adding u additional variables is to be tested using the usual formula

$$F = \frac{(R_{t+u}^2 - R_t^2)/u}{(1-R_{t+u}^2)/(n_1+n_2-(t+u)-1)}$$

R_t^2 is here the multiple r between the dichotomous variable—'being opened' or 'being closed'—on the one hand, and the t possible independent variables, globe temperature, air temperature, etc. on the other. F is to be tested for significance with u and $n_1+n_2-(t+u)-1$ degrees of freedom.

R_t^2 and D_t^2 are related as

$$R_t^2 = \frac{\alpha D_t^2}{1+\alpha D_t^2}$$

Table IV

	$\bar{T}_{sa}$ (opening) K	$\bar{T}_{sa}$ (closing) K
All year	−0·79	−0·09
Winter	−0·83	−0·12
Spring	−1·04	−0·24
Summer	−0·60	−0·05

where

$$\alpha = \left(\frac{n_1 n_2}{n_1 + n_2}\right) \frac{1}{n_1 + n_2 - 2}$$

(If $n_1 = n_2 \gg 2$, α tends to 0·25. See Porebski (1966, equations (41) and (47)) for the relation between R^2 and D^2.)

Using the all-year data, air temperature with its $C_1 = 0{\cdot}4677$ was successively combined with all the other variables. The largest resulting D^2 was 0·7704 (provided by combination with ceiling temperature for which $C_2 = 0{\cdot}048$ and $r = 0{\cdot}831$). With $n_1 = 163$ occasions of opening, and $n_2 = 154$ occasions of closing, $R_1^2 = 0{\cdot}05212$ and $R_2^2 = 0{\cdot}12983$, and we find a value of $F = 28$. To reach significance with 2 tests -1 test $= 1$ d.f. and $163 + 154 - 3 = 314$ d.f., F must exceed 254 at the 5 per cent level of probability to be deemed 'significant'. The computed value of F is 28, thus indicating that ceiling temperature cannot provide any information on the probability of opening or closing windows other than that which is provided by air temperature alone. This applies to all other variables.

5. DISCUSSION

What features of the microclimate are associated with classroom windows being open or closed? In this study room air temperature appears as the main, indeed the only, environmental correlate. The study shows however that to describe the data adequately, we have to answer a related question: *when* do people open windows? In the Wallasey classrooms windows tend to be opened early in the school day and to be closed again towards its end. Thus the overall probability of finding one or two windows open can be expressed as the product of two independent probabilities, one based on air temperature, the other on time of day. Figure 1(a) shows the dependence of window opening on air temperature very reliably, Figure 1(b) shows the same effect somewhat less reliably but removing the time of day component. Figure 4 indicates that the time of day effect persists within separate high, medium and low air temperature bands.

The discriminant analysis compares microclimate conditions prevailing at the time occupants opened windows with those when windows were closed. Once again air temperature emerges as the most discriminating single variable. No other variable combined with air temperature improved discrimination significantly. As discussed previously the surface–air difference T_{sa} which does discriminate significantly between the 'make open' and 'make closed' conditions does so as an artefact. It is likely that the same artefact underlies relationships between T_{sa} and judgements of environmental 'freshness'. When windows are opened T_{sa} moves from negative to positive, and concurrently air movement increases, leading to greater convective and evaporative skin cooling. Thus the relation between T_{sa} and freshness is not direct but due to the dependence of each on window opening.

The present data provide no support for the view that relative humidity is a factor motivating people to open windows in the class room. In other environments, of course, there could be such an effect. It is not possible to demonstrate any dependence on odour levels. However, windows are opened predominantly in the first hour or so of occupation and it may be that on some occasions the wish to rid the room of a smell may have been a factor. The authors during numerous visits to the school have rarely if ever been troubled by odour levels. Odour problems were mentioned, however, by individual children in the cross-sectional user survey (Davies and Davies, 1971) but no systematic odour data have been collected.

Finally, it may be mentioned that occupants' window opening behaviour demonstrates the expected adaptational (hysteresis) effects. Windows are opened at higher temperatures than they are closed. Thus although high air temperatures may be said to cause people to open windows adaptational effects and diurnal habits have to be taken into account as well.

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REFERENCES

Brundrett, G. W. (1977). 'Ventilation: a behavioural approach', *Int. j. energy Res.*, **1**, 289–298.

Davies, A. D. M. and Davies, M. G. (1971). 'User reaction to the thermal environment—the attitudes of teachers and children to St. George's School, Wallasey', *Building Science*, **6**, 69–75.

Davies, A. D. M. and Davies, M. G. (1987). 'The passive solar heated school in Wallasey. VI. Thermal sensation and comfort in the classroom: a year-long study of the subjective and adaptive responses of children', *Int. j. energy Res.*, **11**.

Davies, M. G. (1970). 'The performance of the linear discriminant functions in two variables', *Brit. J. Math. Stat. Psychology*, **23**, 165–176.

Davies, M. G. (1986). 'The passive solar heated school in Wallasey. IV. An observational study of the thermal response of a passive school building', *Int. j. energy Res.*, **10**.

Dick, J. B. and Thomas, D. A. (1951). 'Ventilation research in occupied houses', *J. Inst. Heat. Vent. Engrs.*, **19**, 306–326.

Fisher, R. A. (1936). 'The use of multiple measurements in taxonomic problems', *Ann. Eugen.*, **7**, 179–188.

Porebski, Olgierd R. (1966). 'On the interrelated nature of the multivariate statistics used in discriminatory analysis', *Brit. J. Math. Stat. Psychology*, **19**, 197–214.