ROOM ORIENTATION AND HEALTH IN NATURALLY VENTILATED BUILDINGS

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ABSTRACT

Orientation of opening windows of 48 buildings in south-east Australia is related to occupant complaint of sensitivity to the indoor environment. Where certain rooms were reported as being worse than others in the same building, nearly all orientations were leeside of winds prevailing in Melbourne. This trend was also evident for bedrooms of complaint persons, but not for a small sample of comparable bedrooms in non-complaint houses. The possibility that these rooms are under-ventilated despite construction not being deliberately air-tightened is discussed, along with design implications for healthier warm climate buildings.

INTRODUCTION

In the northern hemisphere, the phenomenon of health being affected by indoor pollutants has been increasingly noted and investigated since the 1970s, particularly in cold climate countries. In Australia, similar investigations began much later, with the first survey of common indoor air pollutants in housing published in 1988. The survey (1) was of 140 dwellings in and around Sydney, the largest Australian city. Findings indicated that Australian housing may not be as free of indoor air quality problems as its reputation for buildings which "leak like a sieve" and its warm climate would suggest.

The possibility exists that Australians have had indoor air problems in housing in the past two decades; but unlike inhabitants of colder climate countries they have not had the opportunities for detection and definition given by the sudden increase in the price of heating oil in 1973 and the widespread air-tightening of buildings which followed. Most Australians live in the south-east coastal regions where heating is required in winter, but outdoor temperatures are not very low, as shown in Figure 1. Reduction of air infiltration in south-east Australian housing was investigated and reported in 1986 (2) as unlikely to be cost effective in the majority of cases, despite the fact that it was measured to be about twice the values for groups of housing in the United Kingdom, The Netherlands and New Zealand, and six times values in Canada and Sweden. However, it is possible that, as in New Zealand (3) infiltration of outdoor air has been unintentionally reduced by changes in housing construction and materials in recent years. Any problems arising might be expected to be typical for low-rise, detached small buildings with intermittent or non-existent mechanical ventilation, in warm climates.

This paper presents some findings of an investigation into 48 small buildings between 1981 and 1988, mainly dwellings in and around Melbourne. In almost all complaint buildings, the complaint was initially expressed not in terms of the building, but as the problem of an individual occupant who had become unusually sensitive to the indoor environment. Given the general lack of definition of building-related health problems in Australia at the time, this form of complaint was not inconsistent with some problems being partly or wholly caused by factors in the built environment. This was supported by the fact that most participants had lived in their dwellings for a number of years. It was considered that, as many symptoms reported were similar to those listed in "sick building" investigations in other countries, this group of buildings might include a higher proportion of typical Australian problem buildings than would be found in a random sample.

The first three rooms investigated had opening windows or large fixed vents facing in a NNE direction, suggesting that occupant complaint might be a function of room orientation. Further investigations showed a bias in the orientation of opening windows of rooms often occupied by the complaint persons to the east rather than the west half of the compass. This led to the hypothesis that an effect of wind and ventilation was indicated, rather than sun and overheating which is most typical of NW to W facing rooms, because easterly winds are infrequent in the Melbourne region. The under-ventilation of rooms on the leeside of buildings has been particularly evident in The Netherlands (4,5,6). While south-east Australia is generally higher above sea level with topography more undulating than The Netherlands, it was considered possible that a similar wind effect could also be increasing occupant exposure to indoor pollutants in the Australian housing studied.

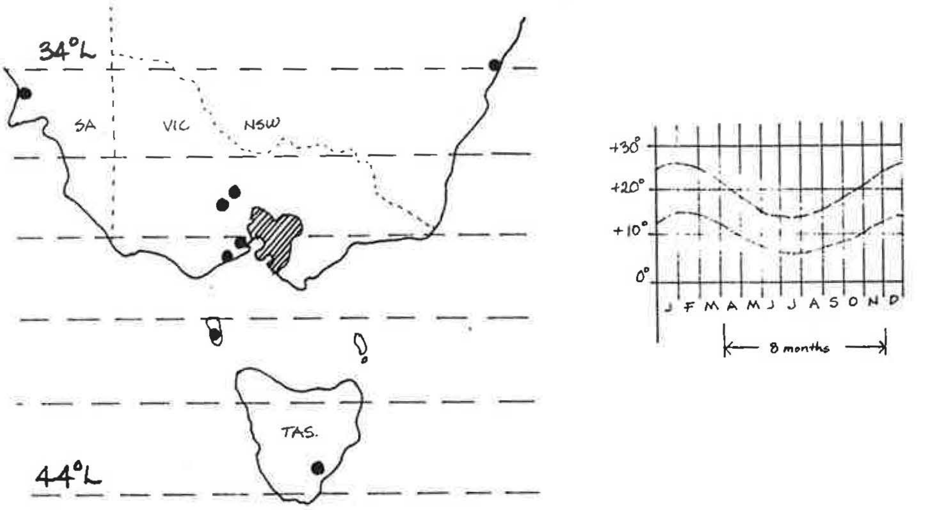

Figure 1. Map showing Melbourne East Central meteorological district (hatched) where 40 buildings were located, and sites of buildings outside the district.
To right:- Mean daily maximum and minimum temperatures (centigrade) for each month in Melbourne. Source: Climatic Averages Australia, Canberra.

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METHODS

The 43 buildings associated with complaint were self-selected. Their occupants in all cases approached the investigator for architectural assistance in making an environment in which symptoms would decrease. Many were recommended by health practitioners after other treatments had not brought about satisfactory improvement. In the five non-complaint buildings, the investigator approached the occupants. Unlike the former group, these occupants reported either no environmentally related symptoms, no worsening of such symptoms or an improvement in health since living there. Without any reference guidelines for typical Australian problem building characteristics, it was decided to check a broad range of factors in each case. The emphasis was on identification of as many potentially building-related health problems as possible through building inspection and occupant interview, rather than by technical measurement of specific indoor pollutants. Although many participants were planning to move and had consequently lost interest in improving their existing environments, these buildings were checked on the same basis as those in which occupants planned to stay. The checklist of items increased as the investigations progressed. This approach was considered appropriate given the early stage of research in the field.

One of the most difficult tasks was to make a connection between symptoms and specific physical environments. For instance, only one complaint (case no.1) was made in terms of the building, a "lack of ventilation in two meeting rooms with overheating in summer in one of them". Even a workplace complaint (case no.2) was, like all other complaints associated with the dwellings, initially made in terms of a particular occupant's hypersensitivity to air pollutants. In order to make some connection between symptoms and changes in the built environment, all complaint persons were encouraged to name places, both indoor and outdoor, which they associated with changes in symptoms. In eight cases, occupants reported certain rooms to be worse than others in the same building. This first group is identified as buildings with "complaint rooms". The orientation of openings in these rooms was recorded relative to opening windows in all other habitable rooms. The pattern formed was used as a basis for comparison of room orientation in the second group, which consisted of 35 dwellings of "complaint persons". Orientation of all openable windows in complaint person's bedrooms relative to all other bedroom windows was compared, as the bedrooms were one part of the dwelling known to be occupied eight to twelve hours out of twenty-four. A similar comparison was made of bedrooms of occupants considered most prone to sensitivities or of the only bedroom in use, in the third group of five cases identified as "non-complaint" dwellings. In order to see whether east-facing rooms might have been deliberately chosen by the most sensitive occupants for morning sunshine, the bedroom allocation in each house was checked for deviation from the usual pattern of "couple or household head in the master bedroom".

In all 48 cases, data collected included length of stay in the building, location of complaint room or complaint person's bedroom, site and floor plan, and daily presence of smokers in the buildings. As major sources of pollutants indoors and out could tend to mask any ventilation effects related to room orientation, all cases were checked for two readily identified sources. These were smoking within the building, and traffic pollution as indicated by traffic lights at an intersection in major traffic routes or freeways within 750 metres of a dwelling. Two cases, where the occupants had stayed less than one month in the dwelling were indicated separately, as it was reasonable to expect no pronounced effect of these buildings on long term health problems. Wind sheltering of windows by obstructions such as wing walls and fences has also been omitted from this analysis, as obstructions at a greater distance can cause similar effects but had not been recorded on site plans.

Orientation of windows is given corrected to intervals of nine degrees, with readings from street maps preferred over title plans where minor discrepancies occurred. This choice was made so that the dominant grid of Melbourne's roads, to which many buildings are aligned, could be readily identified in the orientation diagrams. Orientation of opening windows only has been used, rather than including that of fixed venting. The one exception is case no. 1 where eight large pairs of fixed vents, overlapping in inner and outer walls, were similar in ventilation area to some open windows. Otherwise it was assumed that the area of fixed vents was much less significant to indoor air flow than even slightly open windows, particularly as many vents were blocked by internal painting or external vegetation and cobwebs. Also vents were not considered comparable with each other, some being paired, some offset, and others appearing in outer or inner walls only. Similarly infiltration around window architraves was also considered of little relevance to any room orientation effects, particularly as most rooms studied had only one window wall.

The three room orientation diagrams were checked against weather data for the Melbourne Regional Office. This was selected as most buildings studied were in the general region, afternoon wind records had been made over a long time, and the pattern of wind direction frequencies did not differ markedly from that of the nearest airport. It was assumed that the number of cases studied was large enough for local differences in shielding factors not to greatly influence any overall pattern. Leesidedness of various orientations was estimated by averaging the frequencies of the three winds most likely to bring the opposite side of an unobstructed rectangular building under positive pressure. Winds incident on the windward wall from about 65 degrees or closer to right angles are most likely to cause positive pressure on a windward wall (7). Three such winds were identified from the eight wind directions given, and "leeside frequency" was calculated for eight possible orientations for the wall on the far side. This was done for the eight months of the year when mean daily maximum temperatures fall below 22 degrees centigrade and occupants are more likely to close windows often for comfort reasons. In this approximation, wind influence on flank walls was disregarded as they were considered more likely than the far wall to come under positive pressure from wind reflections off other lowrise buildings, as shown by Häggkvist et al (8) in a group of detached small buildings.

Binomial statistical tests were applied to each of the first two orientation diagrams, comparing the number of opening windows occurring on the N to SE directions compared with the S to NW directions. The main test was a visual comparison of the patterns formed in the first group (complaint rooms) and second group (complaint persons), then of both with the "leeside frequency" weather data.

RESULTS

The Buildings

Forty of the buildings, including the five non-complaint dwellings, were located in Melbourne East Central meteorological district as shown in Figure 1. This reflects to a large extent the locations of the medical practices referring patients to the house investigations. Two buildings were in country Victoria, two in or near Geelong, two in Tasmania, one in Sydney and another in Adelaide. In the group as a whole, 42 were detached buildings and 34 were single storey. Only one dwelling,

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built before 1900, had a basement. About one third of all buildings were initially constructed before 1960, and only three were constructed after 1982, when the Victorian Uniform Building Regulations no longer required fixed external vents to all rooms. Houses built after the 1960s tended to have lower ceiling heights and lower roof pitches, more concrete slab-on-ground floors than the older houses, and to have top-hung windows. Eight complaint and three non-complaint buildings had concrete floors. The remainder had elevated timber floors, in ten cases with under-floor ducted heating. Most dwellings had between two and five bedrooms, and were over 150 sq. metres in floor area. They were generally large by European standards and at low site densities. Several were in open farm landscape, but most were in areas with between two and sixteen dwellings to the hectare. Only three cases were in areas where building heights were permitted to exceed two storeys. Detached housing and planted gardens appeared randomly planned with little regard to orientation. Building shapes were generally complex and different from each other. Solid fences of about 1.6 metres height, usually of timber palings, were common on three and sometimes all boundaries of allotments.

Most buildings were brick veneer and over half had top-hung wooden sash opening windows. Gas stoves, most without ducted mechanical exhausts, were in thirteen of the complaint houses and had been recently removed from a further three. Three of the five non-complaint houses had gas stoves, only one of them with a ducted exhaust fan, which was infrequently used. There were no unvented combustion sources such as flueless gas or kerosene heaters in any houses. Twenty-five of the complaint buildings and none of the non-complaint houses had a readily noticeable damp problem. About half of them were mild to moderate, such as visible mould in bathrooms, a generally musty smell, or condensation on bedroom windows. Others were more severe, such as floor settlement due to excessive subfloor wetness. In thirty of this group, and none of the non-complaint dwellings, a distinctive odour considered "unacceptable" by the investigator was evident (in three buildings the odour of napthalene dominated). In several cases occupants reported having little or no sense of smell.

Occupants

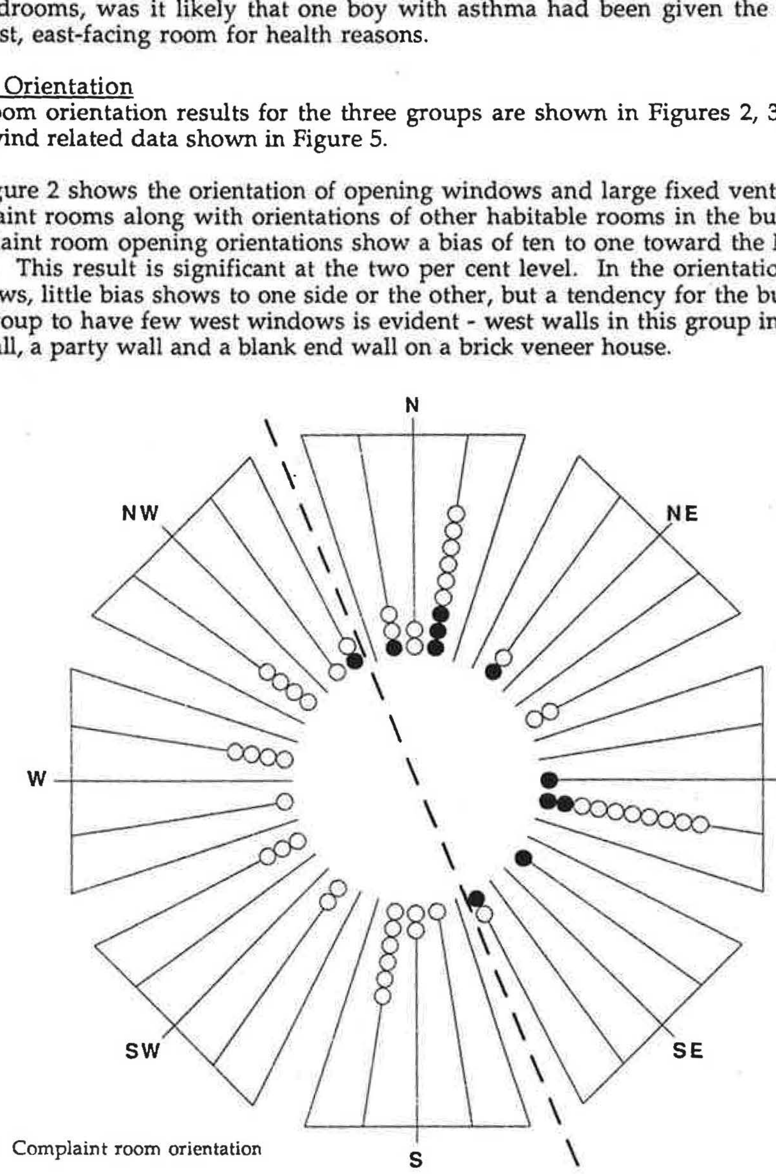
Most complaint buildings were occupied during the daytime, in many cases because the complaint person was no longer working due to symptoms. Most of the non-complaint buildings were also occupied during the daytime, due to home based employment. In some of the complaint buildings occupants reported not opening windows for a variety of reasons - acoustic privacy, road noise, an association of outdoor air with pollution sources, security, child safety, and in three cases because the windows had jammed. Most, however, reported keeping windows open often, especially slightly open in bedrooms overnight. A few kept windows wide open often, to the point of thermal discomfort. None had deliberately air-tightened the building for energy conservation except in one non-complaint house occupied by a heating and ventilation engineer. Many others, however, had made different modifications to the home environment in order to relieve symptoms. Reports of the effectiveness of such measures varied greatly. Modifications included changing window opening procedures, removing carpets, removal or disuse of gas stoves and underfloor ducted heating systems, substitution of gas space heaters with portable electric heaters or of oil-fired heaters with wood-fired heaters. Occasionally bedrooms, and in two cases kitchens, were seen as retreats for the sensitive persons, and kept closed off from the rest of the dwelling. In twenty of the complaint dwellings, occupants expressed doubt that the built environment could be made suitable for their special requirements and were considering moving house. The ideal of building a new house of carefully chosen materials was often expressed.

Bedroom allocation in nearly all dwellings had been determined by a couple or single head of a household taking the largest or master bedroom. With children, girls tended to have the larger rooms with pleasant outlook, and boys the narrower, smaller rooms to the back or side of the dwelling. In only one case, a house with ten bedrooms, was it likely that one boy with asthma had been given the largest, sunniest, east-facing room for health reasons.

Room Orientation

Room orientation results for the three groups are shown in Figures 2, 3 and 4, with wind related data shown in Figure 5.

Figure 2 shows the orientation of opening windows and large fixed vents in the complaint rooms along with orientations of other habitable rooms in the buildings. Complaint room opening orientations show a bias of ten to one toward the N to SE sector. This result is significant at the two per cent level. In the orientation of all windows, little bias shows to one side or the other, but a tendency for the buildings as a group to have few west windows is evident - west walls in this group include a fire wall, a party wall and a blank end wall on a brick veneer house.



● Complaint room orientation

○ Orientation of all other habitable rooms

Figure 2. Orientation of opening windows and large fixed vents in buildings with complaint rooms.

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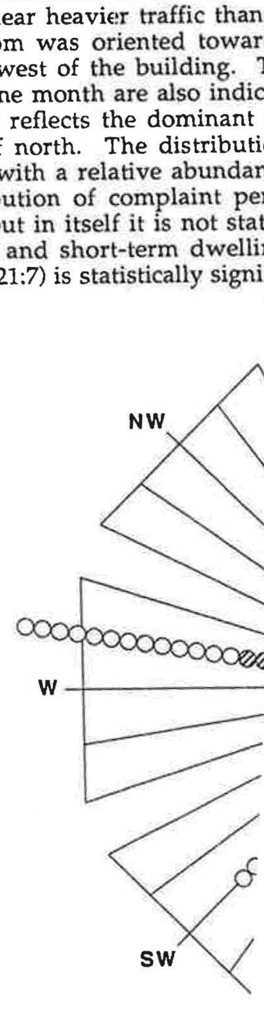

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◍ Smoking in dwelling

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Figure 3. Orientation of
dwellings.

The orientation of opening windows in bedrooms of the most sensitive occupant of each dwelling in the complaint person group, is shown in Figure 3. Marked circles indicate bedrooms of complaint persons, and unmarked circles indicate all other bedrooms in the dwellings. Five dwellings had smokers. Three dwellings were near heavier traffic than others, and in all three cases the complaint person's bedroom was oriented toward the apparent air pollution source, on the west or south-west of the building. The two dwellings which had been occupied for less than one month are also indicated. The pattern shown by all bedroom orientations clearly reflects the dominant street grid of Melbourne's suburbs, which is slightly east of north. The distribution of bedroom windows to east and west is almost even, with a relative abundance of west windows unlike the previous group. The distribution of complaint person's bedroom orientations (23:15) shows a similar bias, but in itself it is not statistically significant. When the sub-group of smokers, traffic and short-term dwellings is eliminated, however, the resulting orientation ratio (21:7) is statistically significant at the two per cent level.

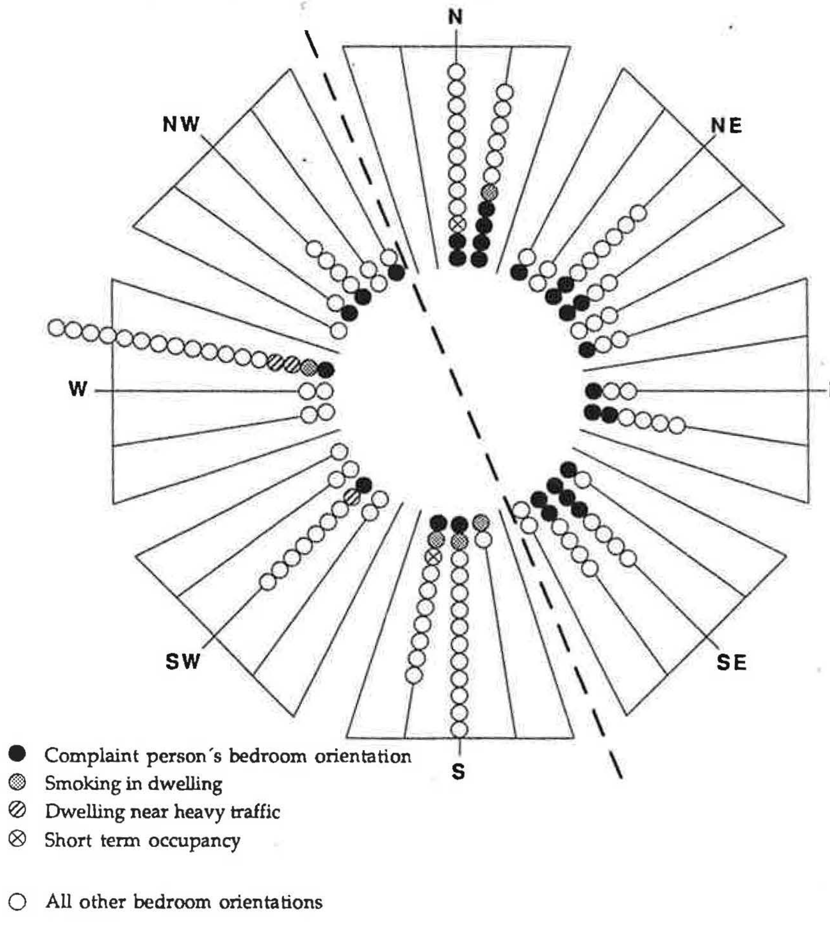

Figure 3. Orientation of opening windows in bedrooms of complaint person's dwellings.

In the small group of non-complaint dwellings, no bias of window opening orientation of either bedroom category can be seen. The only pattern is a tendency to reflect a similar street map pattern to the other two groups.

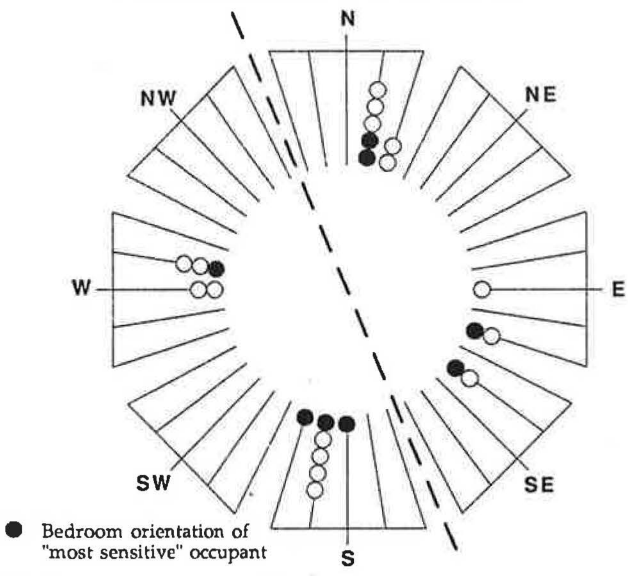

Figure 4. Orientation of opening bedroom windows in non-complaint houses.

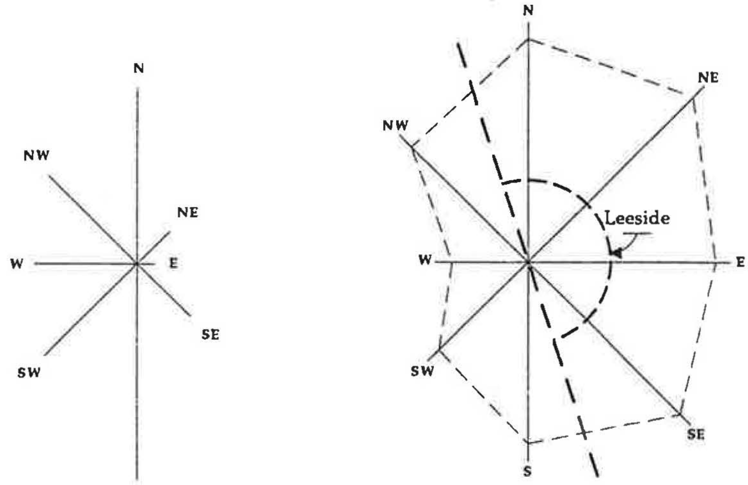

Figure 5. Wind frequencies at 3 pm from April to November for Melbourne Regional Office (Source: Bureau of Meteorology, Victoria). To right:- "leeside frequency" diagram (scale enlarged for clarity).

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Overall, a pattern of east-biased orientation shows clearly in the complaint room orientations, less strongly in the complaint person's bedrooms, and not at all in the non-complaint group. A major difference between sectors for both the first and second groups is evident when complaint orientations are divided by a line running from NNW to SSE. The position of this line is close to the dotted diagonal line estimated to divide lee and windward sectors for Melbourne's cooler months, as shown in Figure 5. Of the four buildings outside Victoria only one, in Sydney, showed westerly orientation of the complaint person's bedroom.

DISCUSSION

Building Characteristics

As a group the complaint buildings appeared very diverse in age and construction materials, except for a prevalence of timber floors. This was a contrary finding to that of the investigation of 140 Sydney dwellings (1), where concrete slab-on-ground floors were associated with lower rates of air exchange. Other characteristics associated with poor indoor climate in the Sydney study, such as unvented gas heaters, were not present. Gas stoves, while generally poorly vented, were present in less than 40% of dwellings, well under the Melbourne rate of 61% during 1986 (9). The non-complaint dwellings, while a small in number, indicated that unvented gas stoves and concrete slab floors do not necessarily contribute to occupants reporting sensitivity to indoor environments. These houses were, however, unlike the complaint dwellings in that most had more than one wall with opening windows in comparable bedrooms.

The results of this investigation suggest that problem buildings in south-east Australia, at least in the Melbourne region, may have design characteristics in common, rather than materials and construction types. Occupant complaint of hypersensitivity to the indoor environment was linked with the reporting of leeward rooms as worse than others, and a tendency to occupy bedrooms with a single window wall on the leeward side of dwellings. The latter tendency appeared stronger in dwellings without readily noticeable pollution sources.

One unusual factor in the group of 48 buildings was the relative absence of daily tobacco smoking in the complaint buildings, and its total absence in the non-complaint dwellings. This gave an opportunity to study factors which might be less apparent when masked by effects of smoking indoors. Two apparently prevalent characteristics in the 43 complaint buildings were distinctive indoor odours (30 cases) and damp problems (25 cases), especially when compared to the absence of both factors in the five non-complaint dwellings. Both observations are suggestive of low ventilation rates for the complaint dwellings or some parts of them.

Under-ventilation of Leeside Rooms

The tendency for leeside rooms to be under-ventilated while the air exchange rate in the house as a whole is adequate has been found in Dutch housing (4). Measurements were made continually during a gradual 360 degree change in wind direction. Rates as low as 0.25 air changes per hour were measured for lee bedrooms with closed doors, while the whole house measurement stayed consistently close to one air change per hour. The effect is explained in terms of a tendency, in the absence of mechanical ventilation or of very low outdoor temperatures, for the ventilation pattern to be determined by wind-dominated rather than buoyancy-dominated air flow. Variations depend on weather conditions, shape, construction and situation of a dwelling as well as the position and size of openings and the actions of occupants themselves. The climate of south-east Australia (latitude 30 to 45 degrees) is warmer than that of The Netherlands (latitude 50 to 54 degrees), and dwellings are typically larger, single not double storey, and at comparatively low site densities. Buoyancy-dominated airflow tends to occur more in taller buildings, especially when there are considerable differences in indoor and outdoor temperatures. Wind-dominated ventilation patterns can thus be expected to an even greater degree in Australian than in Dutch housing. One effect may be that it is not necessarily whole houses that are under-ventilated, but parts of them such as rooms with leeside or wind-sheltered external walls. Such a phenomenon might contribute to the reporting of symptoms in terms of certain occupants rather than the building, as found in this study.

Whole-House Air Flow

When air exchange is wind-dominated, low overall rates in houses may be due to wind-sheltering of the whole building, rather than to infiltration opportunities provided by the construction. Lower whole-house air exchange rates have been associated with newer housing in Australia, such as slab on ground construction and solar housing (1,2). This may relate to the practice of excavating house sites so that the concrete floor slab is laid on cut earth not fill, not only to the elimination of cracks in flooring or vents in walls. The whole house may thus have been brought down out of the main zone of wind influence. Such lowering of floor levels on sloping sites has become more common since the 60s in both concrete and timber floored housing, along with the lowering of ceiling heights. These changes can be shown to have brought the window opening level (around sill height for a slightly open top-hung window) two to four metres lower than in a typical 1950s house with elevated floors and double-hung windows. Wind influence may be comparatively less on all walls for houses on sloping, excavated sites.

Biggs et al (10) in a study of seven unoccupied suburban Melbourne houses, found buoyancy airflow of negligible importance to air infiltration. Instead, results correlated well with Bureau of Meteorology wind speed data, variations being explained by wind-directional sensitivity in four of the houses. One of the houses had a continuous brick wall with weather stripped external door on the western face, and showed lower whole-house air infiltration when the wind was from the west. The floor plans of three of the eight "complaint room" buildings in this study showed a similar lack of sensitivity to west winds.

From Figure 5 it can be seen that while west winds are not the most frequent winds in Melbourne, the westerly wall of an unsheltered building may be least often leeside of all the eight directions. The presence or absence of westerly openings may be significant both to overall levels of indoor pollutants and to their distribution within buildings. Even if Australians follow the general pattern found in cooler countries (11) of opening windward windows less than leeward windows for comfort reasons, infiltration at a considerable level could still occur often on west walls around architraves and vents. Pollutants thus redistributed to leeward rooms might include water vapour, depending on the floor plan and location of wet areas, as has been found in naturally ventilated German apartments (12). Increased tightness in Danish dwellings was associated not only with higher levels of gaseous pollutants, but with higher humidity and dust mite levels (13). In some of the dwellings studied here, dampness could have been contributing to similar problems, not necessarily due to low rates of air exchange but to redistribution of moisture in the building toward leeward bedrooms. Such whole-house effects must be considered in conjunction with possible under-ventilation of leeside rooms.

Influence of Occupants

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Influence of Occupants

Occupant behaviour in these dwellings was not necessarily generally typical, as in many cases steps had been taken to make the environment healthier. It is possible that some of the modifications, taken from books of advice for colder climates, may have had the opposite effect to that intended, especially reduction of heating levels and closing off rooms as retreats for hypersensitive individuals. Such behaviours may have influenced the process of self-selection in this sample, increasing the numbers of those who reported their symptoms to be getting worse no matter what they did. One explanation for this is that, because most were already occupying rooms with a tendency to be under-ventilated, the modifications in certain dwellings actually increased exposure to indoor pollutants by reducing air-flow further. The tendency for complaint persons to occupy rooms on the lee rather than windward side of buildings may be an indication of the conditions under which apparently sound "healthy building" advice does not work in warm climates.

Climate Influence

Australians and others in warm climate countries may be experiencing indoor air problems due to restricted airflow just as was noted in colder climates, but with an effect far less easily related to building characteristics unless design features, occupant behaviour, and wind sensitivity of particular buildings and rooms is taken into consideration. By contrast, health effects due to low air exchange in cold climate countries are more obviously linked with permanent features of a building such as mechanical ventilation or tightness of construction. The discovery of indoor air problems in Australian buildings and those of other warm climates may be hindered by the expectation of similar phenomena, especially by preoccupation with the tightness or otherwise of buildings. Yet even in colder climate buildings where buoyancy-dominated ventilation patterns prevail for most of the year, wind influence can be considerable. In Sweden, under-ventilation of leeside rooms has been proposed as a possible contributing factor in some types of sick buildings (14) such as where balanced ventilation systems are used.

Design Implications

In The Netherlands the under-ventilation of certain bedrooms became readily evident (15) because with prevailing winds from the south-west, solar orientation of living rooms meant that most bedrooms were placed on the leeside (north-east). In Australia, the larger, single storey dwellings planned with more bedrooms and less regard for orientation would tend to make any similar effect more difficult to detect. Yet the design opportunities for both windward facing bedrooms and solar oriented living areas are greater. With the change of hemisphere, the direction of solar gains (north-east to north-west in winter) is reversed while frequent winds, at least for the Melbourne region, are similarly south-west.

In other warm climate countries, a similar opportunity to locate rooms requiring higher indoor air quality away from frequently leeside or wind-sheltered locations may exist for many sites, without necessarily compromising solar design possibilities. In existing buildings, the same principle may be tested by reallocating use of rooms, with longer-occupied areas to windward and rooms with lower air quality requirements such as storage, wash rooms and smoking areas, to the usual leeside. This approach to healthier warm climate buildings may be far more economical than applying typical cold climate solutions such as extreme care in the selection of building materials, filters and air-handling systems. It requires, instead, reliable methods of determining typical on-site wind conditions, understanding of likely user behaviour, and an informed building designer.

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LABORATORY AND
THE DES
VENT

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Heat sources within a building lead
using the "stack effect". These buoyancy-
in this paper. Water-filled laboratory m
concentrations representing air at differen
models is given, together with the scalin
of a mathematical model is also given,
modelling techniques are applied to a pro

Natural ventilation is the use of na
pressure differences may be caused by th
external air. It is the latter type of natur
Though wind-driven ventilation is impo
observed on calm days, and will not be c
of natural, rather than mechanical, vent
such as atria (1). Clearly the use of no
design stage.

In section 2 of this paper we desc
temperature differences, using water-
different temperatures. In section 3 w
this model is given in (2)). The appli
Humanities at the University of Sevil
with a discussion of the general feature

2. LABORAT

2.1 Scaling Laws

For the ventilation flows consid
from the values of the Reynolds and
UL/κ respectively, where U is a ty
diffusivity of heat. At such large va
scales. To simulate these flows in
Péclet numbers in the experiment a
models using water as the working fl
concentrations represent different ten
in water that gives the relevant Péclo

The driving force in these flows