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NICE BUILDING: PITY IT'S NOT VERY COMFORTABLE

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ABSTRACT

Development of mechanical vapour compression refrigeration in the 20th century and of a steady state theory of human comfort in the 1970s offered the promise of an ideal indoor climate for everyone. The idea of sealed, mechanically ventilated, cooled and heated buildings was promoted heavily by the air conditioning industry and was adopted with enthusiasm by the architectural profession and the real estate industry as a release from climatic design constraints and an opportunity for risk avoidance. By the mid eighties however realisation was dawning that not everybody considered the same indoor conditions "ideal" and not everybody was satisfied with mechanical ventilation. At the same time concern was developing for the effect on the atmosphere of unbridled use of energy derived from fossil fuels and an interest began to develop in design for passive ventilation strategies and adaptive theories of thermal comfort. The debate continues with evidence that many sealed air conditioned buildings fail to provide the comfort and satisfaction intended whilst contributing significantly to the greenhouse effect. The author has collected subjective responses to their indoor work environments from 1213 occupants of 26 office settings in 24 buildings. Six are naturally ventilated and three of these have occupant controlled supplementary cooling and heating systems. The remainder are air conditioned. One of the naturally ventilated settings with supplementary cooling and heating (number 16) is located in the Architecture building at Sydney University and its energy consumption has been recorded for more than two years. Some results of the surveys and of monitoring energy consumption of setting number 16 are presented in this paper. Among them are that occupants gave high scores for thermal comfort and air quality to the naturally ventilated buildings with supplementary cooling and heating; and that setting number 16 uses much less energy than would be expected if the space were conventionally air conditioned.

INTRODUCTION

Humankind has sought thermal comfort from the days when early specimens wrapped themselves in animal skins and huddled before fires in caves. Bedford (1948) has pointed out that:-

> *"Man is a very adaptable creature, and can tolerate widely varying conditions. It is true that he can live on the equator or in the Arctic circle, but on the equator he takes shelter from the noonday sun; and if he lives in the Arcitc circle, or even in more temperate climes, he takes shelter from the winds of winter, and clothes himself to preserve his body heat".*

The invention of the hearth made it possible to bring fire into man-made shelters. A big step forward was the chimney which brought a considerable improvement to indoor air quality. Central heating in the nineteenth century provided relatively uniform warmth in winter throughout whole buildings. And finally about a hundred years ago mechanical refrigeration opened the way to construction of the first centrally air conditioned office building in Texas, USA in 1928 where mechanical ventilation with cooling and heating were brought together to provide a fully artificial indoor climate (Guedes, 1979).

Air conditioning of commercial office buildings was promoted heavily by the growing refrigeration industry as a means of providing ideal thermal surroundings for occupants with the added bonus of improved productivity. The concept was embraced by many in the architectural profession as presenting a release from design constraints imposed by climate; and it was taken up enthusiastically by property developers and the real estate industry as a way to reduce financial risk in at least one area.

It was soon realised that research was needed to provide designers with an indication of the thermal conditions that would satisfy building occupants. Bedford (1948) was one of the early investigators who applied a methodical approach to field studies of thermal comfort. As a result of his experiments with women doing light factory work he concluded that it is never possible to please everybody. However he suggested that for comfort *"the equivalent temperature should be 58 °F (14.4 °C) to 66 °F (18.8 °C)."* Nowadays Australian office workers might find this range lower than they would prefer or expect.

The notion of an "ideal" indoor climate was supported by the development by Fanger (1970) of his thermal comfort equation and the concepts of Predicted Mean Vote (PMV) and Percent Predicted Dissatisfied (PPD). These suggested that a single indoor temperature could be selected that would satisfy at least 95 percent of occupants of a building. These concepts are the basis for the current international thermal comfort standard ISO 7730 (1994).

A result not predicted by early protagonists was the effect of a fully controlled indoor thermal environment on energy consumption and its probable contribution to climate change. Oil price crises in the early seventies brought a sharp increase in interest in energy conservation which was mainly focused on improving performance of airconditioning systems. However a few voices rose to suggest alternative strategies relying on natural ventilation through operable windows and doors with or without mechanical assistance.

In 1976 Humphreys analysed a large group of field studies and produced his adaptive theory which related comfortable temperatures to outdoor conditions. The adaptive theory was refined by Auliciems (1981) and has been further refined over many years by Humphreys and Nicol (1998) among others. In a major study commissioned by ASHRAE, de Dear (1998) proposed different relationships between outdoor and indoor comfort temperatures depending on whether the building was air conditioned or naturally ventilated.

The debate continues supported by evidence that many sealed air conditioned buildings fail to provide occupants with the expected levels of comfort and satisfaction and that they contribute significantly to the greenhouse effect and global warming. In recognition of the need to conserve energy in buildings and to improve occupant satisfaction, the International Energy Agency Annexe 35 "Hybvent" project was established in 1998 to explore design strategies for natural ventilation supported by supplementary cooling and heating systems as necessary (Heiselberg, 1999).

As a contribution to the debate, the author has collected subjective responses to a questionnaire designed to explore comfort in the indoor environment. The database includes contributions from 1,213 occupants of 26 office settings in 24 buildings. These data have been collected over the past six years from a sample of Australian buildings, mainly from the Sydney CBD and surrounding suburbs. The sample includes three naturally ventilated (NV) buildings; three settings that are naturally ventilated with supplementary cooling and heating i.e. hybrid (HV); one that is part air conditioned, part naturally ventilated (MM); and seventeen that are air conditioned (AC). It does not include any premium or A grade buildings but is believed to be representative of those which form the bulk of current commercial building stock. Some results related to thermal comfort and perceived air quality are presented in this paper. It was not possible to take measurements of physical conditions in these settings due to funding constraints. However it seems reasonable to assume that in the air conditioned buildings owners and managers will endeavour to maintain optimal conditions to minimise complaints; and in the hybrid examples, occupants will select conditions that suit themselves best.

The following conclusions will be presented:-

- Ten settings including three that are naturally ventilated failed to reach the 50 percentile level of thermal comfort acceptability at the 95 percent confidence level. Five settings including the three hybrid examples scored better than the 50 percentile level at the 95 percent confidence level. The whole population mean is below the 50 percentile level indicating moderate to strong dissatisfaction for more than half the sample.
- Ten settings including one naturally ventilated failed to reach the upper 50 percentile level of acceptability for air quality. The only one that scored better than the 50 percentile level is hybrid ventilated setting 16. The whole population mean is below the 50 percentile level.

- There is a significant dependent relationship between perceived air quality and thermal comfort and between overall comfort and satisfaction and perceived air quality.
- Anecdotal evidence suggests that many occupants appreciate the ability to open windows in pleasant weather when that option is available to them.
- A hybrid ventilation design strategy that provides for occupant controlled supplementary cooling and heating can improve perceptions of air quality and thermal comfort and can result in very substantial energy savings in temperate climates such as occur over much of southern Australia.

METHOD

Questionnaire based surveys of comfort and satisfaction with the indoor environment have been conducted over the past six years in twenty six office settings in 24 buildings, located mainly in and around the Sydney CBC. Selection was ad hoc on the basis of opportunity through contact with the tenant organisations. The buildings and their populations are believed to be representative of a broad cross-section of Australian commercial buildings and their occupants. Whole populations of settings were invited to participate in the surveys where numbers were less than about 100. Where populations were larger a random sample of between 50 and 100 participants was selected. Tenancies surveyed include state and local government instrumentalities, tertiary educational institutions and the private sector.

Participants record on scales from 1 (bad or equivalent) to 5 (good or equivalent) their subjective perceptions of 23 comfort factors spanning the vectors of thermal comfort. air quality, activity related noise, spatial comfort, privacy, lighting and external noise, plus one each for overall comfort and satisfaction and effect on performance of work. This paper will report findings related to the vectors thermal comfort and air quality.

The questionnaire was developed in Canada by Vischer (1989) using a weighted factor analysis technique. Vectors of thermal comfort include “temperature comfort”; ‘how cold it gets?”; “how hot it gets?”; and “temperature shifts”. Air quality vectors are “ventilation comfort”, “air freshness”; and “air movement”. Vector indices are calculated by adding scores for each factor within the vector and taking the population average of the vector total. Thus for thermal comfort scores range from 4 to 20 and for air quality the range is from 3 to 15. The statistical package SYSTAT was used to estimate the 95 percent confidence intervals.

RESULTS

Thermal comfort indices are tabulated in Table 1 and are illustrated in Figure 1 and those for air quality are shown in Table 2 and Figure 2. Mean scores are represented in Figures 1 and 2 as the central points of bars whose length indicates upper and lower 95 percent confidence intervals. Air conditioned settings are indicated by solid bars, hybrid ventilation is indicated by cross hatching and natural ventilation is indicated by open bars. Heavy lines indicate 95 percent confidence limits for whole sample population.

Table 1: Thermal comfort indices for 26 office settings in 24 buildings.

Setting	Number	Lower 95% percent confidence limit	Mean score	Upper 95% percent confidence limit
1	11 (HV)	12.2	14.1	15.9
2	13 (AC)	10.8	13.1	15.3
3	74 (AC)	11.8	12.4	13.1
4	28 (AC)	11.7	12.9	14.2
5	14 (AC)	8.4	10.5	12.6
6	75 (AC)	10.5	11.2	12.0
7	66 (NV)	10.0	10.9	11.8
8	89 (AC)	8.5	9.2	9.8
9	70 (AC)	10.6	11.5	12.5
10	113 (AC)	11.7	12.3	13.0
11	10 (HV)	14.4	16.3	18.2
12	33 (NV)	9.2	10.0	10.8
13	18 (NV)	9.2	10.6	12.0
14	14 (MM)	10.3	12.6	15.0
15	56 (AC)	8.7	9.5	10.3
16	18 (HV)	14.7	16.1	17.5
17	39 (AC)	10.6	11.6	12.6
18	18 (AC)	12.7	14.4	16.1
19	58 (AC)	9.3	10.1	10.9
20	18 (AC)	9.9	11.0	12.1
21	36 (AC)	12.2	13.4	14.5
22	59 (AC)	10.3	11.2	12.2
23	50 (AC)	11.6	12.4	13.2
24	47 (AC)	10.5	11.3	12.0
25	29 (AC)	10.2	11.1	12.0
26	58 (AC)	7.6	8.4	9.1
All	1213	11.1	11.3	11.5

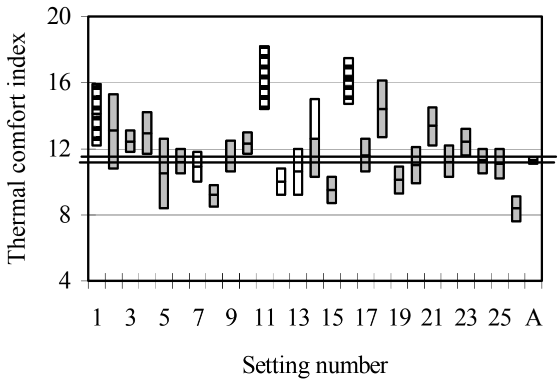

Figure 1: Thermal comfort indices for 26 office settings.

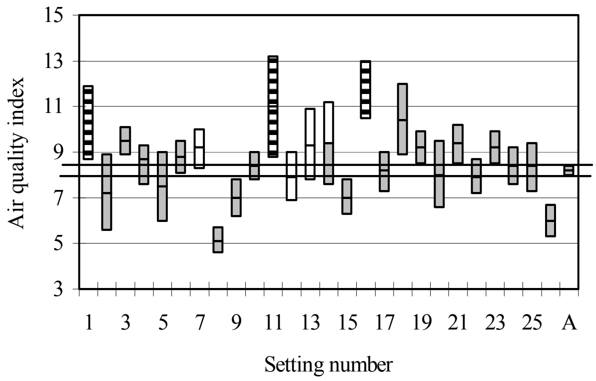

Figure 2: Perceived air quality indices for 26 office settings.

Table 2: Air quality indices for 26 office settings in 24 buildings.

Setting	Number	Lower 95% percent confidence limit	Mean score	Upper 95% percent confidence limit
1	11 (HV)	8.7	10.3	11.9
2	13 (AC)	5.6	7.2	8.9
3	74 (AC)	8.9	9.5	10.1
4	28 (AC)	7.6	8.7	9.3
5	14 (AC)	6.0	7.5	9.0
6	75 (AC)	8.1	8.8	9.5
7	66 (NV)	8.3	9.2	10.0
8	89 (AC)	4.6	5.1	5.7
9	70 (AC)	6.2	7.0	7.8
10	113 (AC)	7.8	8.4	9.0
11	10 (HV)	8.8	11.0	13.2
12	33 (NV)	6.9	7.9	9.0
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21	36 (AC)	8.5	9.4	10.2
22	59 (AC)	7.2	7.9	8.7
23	50 (AC)	8.5	9.2	9.9
24	47 (AC)	7.6	8.4	9.2
25	29 (AC)	7.3	8.4	9.4
26	58 (AC)	5.3	6.0	6.7
All	1213	8.0	8.2	8.4

Overall comfort indices are tabulated in Table 3 and illustrated in Figure 3. Mean scores are at central points of bars whose length indicates 95 percent confidence intervals.

Table 3: Overall comfort and satisfaction indices for 26 office settings in 24 buildings.

Setting	Number	Lower 95% percent confidence limit	Mean score	Upper 95% percent confidence limit
1	11 (HV)	3.7	4.0	4.3
2	13 (AC)	1.5	2.0	2.6
3	74 (AC)	3.4	3.5	3.7
4	28 (AC)	2.9	3.3	3.7
5	14 (AC)	2.1	2.6	3.2
6	75 (AC)	2.6	2.8	3.0
7	66 (NV)	2.9	3.1	3.4
8	89 (AC)	2.1	2.4	2.6
9	70 (AC)	2.8	3.0	3.3
10	113 (AC)	2.9	3.1	3.3
11	10 (HV)	2.9	3.7	4.5
12	33 (NV)	2.0	2.4	2.7
13	18 (NV)	2.7	3.1	3.5
14	14 (MM)	2.8	3.4	4.0
15	56 (AC)	2.1	2.4	2.6
16	18 (HV)	3.2	3.6	4.0
17	39 (AC)	2.7	3.0	3.3
18	18 (AC)	2.9	3.4	4.0
19	58 (AC)	2.8	3.1	3.3
20	18 (AC)	2.8	3.2	3.6
21	36 (AC)	3.3	3.6	3.8
22	59 (AC)	2.8	3.1	3.3
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24	47 (AC)	3.0	3.2	3.5
25	29 (AC)	3.1	3.4	3.7
26	58 (AC)	2.2	2.4	2.6
All	1213	2.9	3.0	3.1

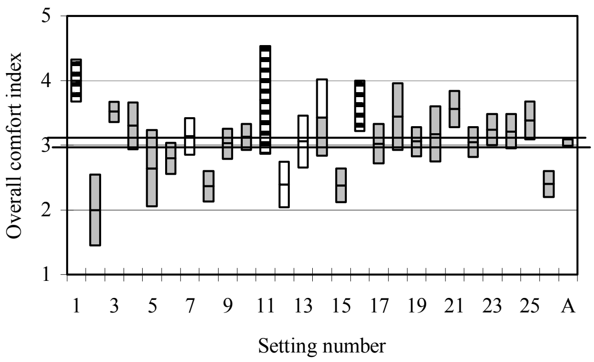

Figure 3: Overall comfort and satisfaction indices for 26 office settings.

Associations are discernible between thermal comfort and air quality indices (R^2 = 0.58, F-ratio = 34.966, P = 0.0005) and between air quality and overall comfort and satisfaction indices (R^2 = 0.65, F-ratio = 46.46, P = 0.0005). These are illustrated in Figures 4 and 5 below.

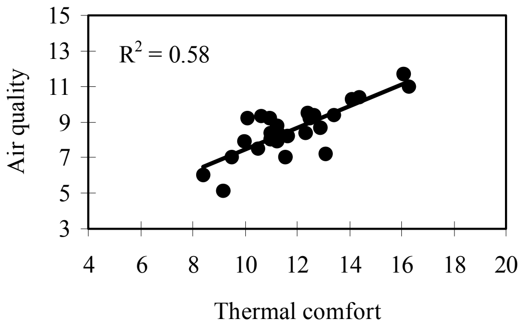

Figure 4: Association between indices for thermal comfort and perceived air quality.

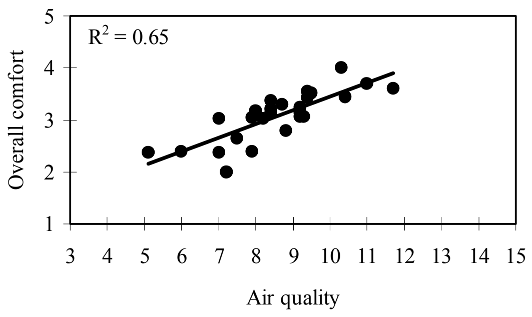

Figure 5: Association between indices for perceived air quality and overall comfort.

Setting number 16 is located in the architecture building at Sydney University. It is naturally ventilated through windows and doors and is provided with refrigerated, occupant controlled cooling/heating equipment by way of fan coil evaporator units in individual rooms. It was possible to survey occupants before (setting 13) and after (setting 16) installation of the supplementary cooling/heating equipment These units remain off (frequently so in mild weather) until started by an occupant to correct discomfort. In other words, the units tend to default to "off". A result of this control mode is a substantial saving in energy used by the system. Also thermal comfort and air quality scores showed significant improvement.

Energy consumed by this system has been monitored continuously since it was put into service in November 1997. The monthly measured consumption has been compared with the consumption that would be expected from a conventional mechanical ventilation, cooling and heating system as estimated by simulation with the energy simulation software ESP II (1985). The results are illustrated in figure 6 below.

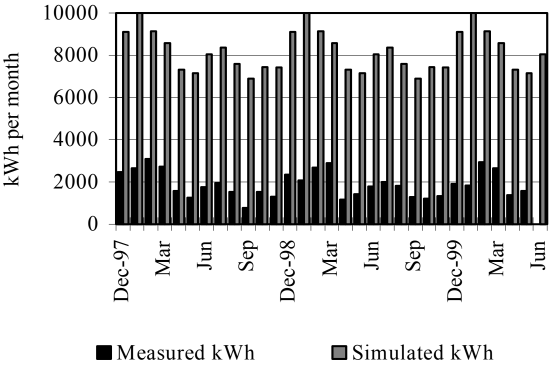

Figure 6. Monthly energy consumption for setting 16 (solid bars) compared with simulated energy consumption for the same setting if conventionally air conditioned with mechanical ventilation, cooling and heating.

DISCUSSION

The indices for thermal comfort and perceived air quality are derived by adding factor scores for each respondent and taking the arithmetic mean of the group total. Thus for thermal comfort, scores over four factors range from 4 (all bad) to 20 (all good) and for perceived air quality, the scores over three factors will range from 3 (all bad) to 15 (all good).

Thermal comfort

Examination of table 1 and figure 1 shows that indices for 10 settings including the three that are naturally ventilated but do not have supplementary cooling/heating did not reach the midpoint score at the 95 percent confidence level. Five settings including all three that are naturally ventilated with supplementary cooling/heating achieved scores significantly above the midpoint score.

It should be noted that the naturally ventilated examples have few if any special passive features of the kind now being designed into modern "sustainable" buildings. Number seven is in a building more than a century old with very heavy masonry construction, high ceilings and tall double hung windows.

A very significant improvement can be observed in the performance of setting 13/16 after provision of supplementary cooling/heating. This building was originally provided with central heating with panel radiators in the rooms which have been retained. It is of heavy weight construction with some rather ineffective shading to windows. The improvement in performance after provision of refrigerated cooling equipment is notable.

Air quality

Ten settings failed to achieve the midrange score at the 95 percent confidence level for perceived air quality and only one, the hybrid setting number 16 achieved a score significantly above the mid point. The whole population score was significantly lower than mid range which suggests that more than half the respondents were moderately to strongly dissatisfied with air quality.

Overall comfort and satisfaction

For the vector of overall comfort and satisfaction, six settings failed significantly to reach the midpoint score while seven, including hybrid settings 1 and 16, achieved better than it. The group mean score was exactly on the midpoint of three, suggesting that approximately half the respondents were moderately to strongly dissatisfied with conditions.

General remarks

Examination of figures 1, 2 and 3 suggests that in terms of occupant perceptions of thermal comfort, air quality and overall comfort the naturally ventilated settings do not differ significantly from many of the air conditioned examples. The availability of on-demand supplementary cooling/heating in the hybrid examples appears to have a significant beneficial effect on the perceptions of thermal comfort and air quality and, to a lesser extent on overall comfort and satisfaction where other vectors are in action.

CONCLUSIONS

It has been shown that at least half of a sample of 1213 occupants of 26 office settings in 24 Australian buildings are moderately to strongly dissatisfied with thermal comfort, air quality and overall comfort in the workplace. Indices for thermal comfort and air quality for ten of the settings failed to reach the mid point of the range at the 95 percent confidence level. It has also been shown that comfort levels can be considerably improved by the provision of occupant controlled supplementary cooling and heating equipment in naturally ventilated premises where occupants can choose between mechanical intervention in bad weather or open windows when conditions are better.

In particular the following conclusions are presented:

- Ten settings including three that are naturally ventilated failed to reach the 50 percentile level of thermal comfort acceptability at the 95 percent confidence level. Five settings including the three hybrid examples scored better than the 50 percentile level at the 95 percent confidence level. The whole population mean is below the 50 percentile level indicating moderate to strong dissatisfaction for more than half the sample.

- Ten settings including one naturally ventilated failed to reach the upper 50 percentile level of acceptability for air quality. The only one that scored better than the 50 percentile level is hybrid ventilated setting 16. The whole population mean is below the 50 percentile level.

- There is a significant dependent relationship between perceived air quality and thermal comfort and between overall comfort and satisfaction and perceived air quality.

- Anecdotal evidence suggests that many occupants appreciate the ability to open windows in pleasant weather when that option is available to them; and to exercise a control mechanism to limit extremes when so required.

A hybrid ventilation design strategy that provides for occupant controlled supplementary cooling and heating can improve perceptions of air quality and thermal comfort. It can also result in very substantial energy savings in temperate climates such as occur over much of southern Australia in comparison with air conditioned premises with fixed windows and mechanical ventilation, cooling and heating..

In a paper referring to the UK experience published in 1984, Finnegan, Pickering and Burge remarked that air conditioned buildings frequently fail to deliver the intended levels of comfort and satisfaction. The findings presented here suggest that the situation is little different in Australia in 2000 A.D.

Nevertheless the real estate industry, developers and tenants generally have been convinced that air conditioning, as conventionally applied to buildings with fixed windows and a uniform thermal environment are necessities of working life in the twenty first millennium.

In the light of the insignificant differences in performance, particularly in relation to overall comfort and satisfaction with the indoor environment, the question must be asked whether the cost of air conditioning is worthwhile. Perhaps the money could be put to better use in improving the passive performance of commercial buildings. It is tempting to speculate that the greater range of opportunities provided in the hybrid settings 1, 11 and 16 provide the context for a full range of adaptive behaviour and consequent improved perception of the thermal environment.

The refrigeration genie is now out of the bottle and will not return to confinement. The possibility of using purely passive technologies to achieve comfort in some climates is undeniable. However these results suggest that in the climate of Sydney with warm humid summers and mild winters, availability of means to limit upper and lower temperature ranges by the use of hybrid technology as required from time to time will significantly improve occupant satisfaction. And it will be accompanied by much lower consumption of energy than in a fully air conditioned alternative.

The three naturally ventilated buildings in this study are not equipped with the sophisticated passive technologies currently being developed by a few enlightened designers for equally enlightened clients. It is hoped that it will be possible in the near future to survey some examples of this genre. The results are anticipated with interest.

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