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# Impact of different building ventilation modes on occupant expectations of the main IEQ factors

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## Abstract

This study explores the relationship between the perceived performance of specific IEQ factors and occupants' overall satisfaction with their workspace. In particular we examine the influence of ventilation system type (i.e. Air-Conditioned AC, Mixed-Mode MM, Naturally Ventilated NV) on that relationship. Statistical analyses were conducted on the post-occupancy survey database from the University of California at Berkeley's Center for Built Environment (CBE) to estimate the relative importance of individual IEQ factors on occupants' overall satisfaction, depending on whether or not the occupants were satisfied with the IEQ factor in question. Based on these analyses, 15 IEQ factors were classified as *Basic Factors*, *Bonus Factors* or *Proportional Factors,* according to their relationship with overall satisfaction, as described in Kano's satisfaction model. We found that the classification of some IEQ factors differed for the occupants of AC, MM and NV buildings, suggesting that occupants of buildings with different ventilation types have different expectations, and respond in different ways to various aspects of the indoor environment. A noticeable difference was in thermal environmental conditions: in NV buildings, good thermal conditions were associated with significantly enhanced overall satisfaction (i.e. strong *positive* impact), but there was little discernible adverse impact, even when thermal performance was deemed to be poor. In AC buildings, on the other hand, thermal conditions were more directly associated with *negative* overall evaluations of workspace by occupants (i.e. greater *negative* impact than *positive* impact). Finally, in MM buildings, thermal conditions exerted both *positive* and *negative* impacts of comparable intensities on overall satisfaction.

## Keywords

Indoor environmental quality, Occupant satisfaction, Kano's model, Adaptive opportunity, Natural ventilation, Thermal comfort

## 1. Introduction

It is not very difficult to find research literature comparing air-conditioned and naturally-ventilated buildings in terms of occupant comfort and the indoor environmental quality (IEQ) provided by those buildings. Occupants in naturally-ventilated buildings are assumed to be more tolerant or *forgiving* of thermal conditions [1]. The thermal comfort zone

is often enlarged as a result of occupants having a certain amount of control over their working environment [2]. And this distinction of occupants in naturally ventilated buildings opposed to air-conditioned buildings can be explained by psychological adaptation which is most likely influenced by thermal history and its effects on expectations [3]. Furthermore, green building rating schemes now in wide use in many countries usually allocate points for individual comfort control (including operable windows) in their IEQ sections [4,5], underlining the commonly held assumption in the commercial property sector that giving an occupant adaptive opportunity to adjust their own indoor climate promotes satisfaction with the workspace and ultimately, productivity.

The primary purpose of this paper is to explore differences between occupants in naturally-ventilated buildings and air-conditioned buildings, focusing on their expectations of what IEQ should be like. Kim and de Dear [6] tested Kano's satisfaction model [7], developed originally in the context of marketing, for its suitability in the context of commercial building occupants' satisfaction with their indoor environment. Then various IEQ factors were categorized as *Basic Factors*, *Bonus Factors* and *Proportional Factors*. This classification depends on occupant expectations of IEQ factors and their differential impacts on satisfaction/*dis*satisfaction, which is described below:

- *Basic Factors* are those that are expected or presumed, thus these are regarded as minimum requirements. Excellence on these factors doesn't necessarily promote occupant's overall satisfaction, but they can cause overall *dis*satisfaction whenever they are deficient in some way. Thus, the absolute magnitude of the impact resulting from under-performance is greater than the impact resulting from positive performance for *Basic Factors*.
- *Bonus Factors* are not normally expected by occupants, so under-performance on these factors is not critical to occupant *dis*satisfaction. But *Bonus Factors* do have a strongly positive effect when they are fulfilled. Thus the impact on overall satisfaction resulting from positive performance is greater than that negative impact resulting from under-performance.
- *Proportional Factors* impact occupants' satisfaction or *dis*satisfaction proportionally, depending on their performance level. When they perform well, occupants will be satisfied, and when they perform poorly, occupants will be *dis*satisfied.

As defined by these three different classifications, the Kano framework has the notion of end-user's (i.e. building occupants in this study) expectations of a product's or service's performance (i.e. IEQ) implicitly embedded in it.
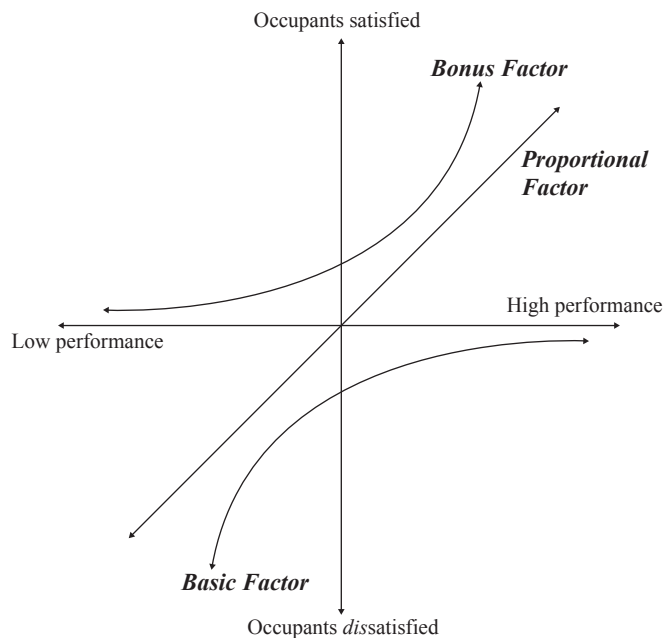
**Fig. 1. Kano's satisfaction model (adapted from reference [7])**

Fig. 1 illustrates the different types of relationship that *Basic*, *Proportional* and *Bonus Factors* have with overall satisfaction. It shows the asymmetric patterns of *Basic* and *Bonus Factors*, depending on their performance level. An implication of this model is that changing occupant expectations could result in a re-classification of IEQ factors between the *Basic*, *Proportional* and *Bonus* categories. In other words, an IEQ factor regarded as minimum requirement (i.e. *Basic Factor*) for one group of occupants could be a *Bonus Factor* for another group, depending on their expectations.

In the following sections, an empirical test is conducted on this hypothesis: *the relationship between perceived performance of specific IEQ factors and occupant overall satisfaction (i.e. Basic, Bonus and Proportional) can differ between occupants of buildings with different ventilation types (AC, MM and NV).* This analysis is followed by a discussion of practical implications, focusing on how different occupant groups respond in different ways to various aspects of IEQ.

## 2. Methods

### 2.1 Data: CBE's IEQ survey database

The Post-Occupancy Evaluation (POE) database from CBE (Center for the Built Environment) at the University of California, Berkeley was used for the analysis in this study. In the CBE survey, respondents express their satisfaction level on a 7-point bipolar scale ranging from 'very *dis*satisfied (-3)' to 'very satisfied (+3)' with various IEQ issues, including thermal comfort, air quality, lighting, acoustics, office layout & furnishings, and cleanliness & maintenance. At the end of the questionnaire respondents rate their *overall* satisfaction level with their workspace, all IEQ aspects considered. Table 1 describes the questionnaire items used in our analysis. The sample buildings are broadly described

as offices, but included educational, public administration and research organizations located in different countries (but mainly in USA).

**Table 1. List of questionnaire items used for the analysis (from CBE occupant survey database)**

| IEQ Dimensions | Questionnaire items | Survey questions |
|---|---|---|
| Thermal comfort | Temperature | How satisfied are you with the temperature in your workspace? |
| Air quality | Air quality | How satisfied are you with the air quality in your workspace (i.e. stuffy/stale air, cleanliness, odours)? |
| Lighting | Amount of light | How satisfied are you with the amount of light in your workspace? |
| | Visual comfort | How satisfied are you with the visual comfort of the lighting (e.g., glare, reflections, contrast)? |
| Acoustic quality | Noise level | How satisfied are you with the noise level in your workspace? |
| | Sound privacy | How satisfied are you with the sound privacy in your workspace (ability to have conversations without your neighbours overhearing and vice versa)? |
| Office layout | Amount of space | How satisfied are you with the amount of space available for individual work and storage? |
| | Visual privacy | How satisfied are you with the level of visual privacy? |
| | Ease of interaction | How satisfied are you with ease of interaction with co-workers? |
| Office furnishings | Comfort of furnishing | How satisfied are you with the comfort of your office furnishings (chair, desk, computer, equipment, etc.)? |
| | Adjustability of furniture | How satisfied are you with your ability to adjust your furniture to meet your needs? |
| | Colours & textures | How satisfied are you with the colours and textures of flooring, furniture and surface finishes? |
| Cleanliness & maintenance | Building cleanliness | How satisfied are you with general cleanliness of the overall building? |
| | Workspace cleanliness | How satisfied are you with cleaning service provided for your workspace? |
| | Building maintenance | How satisfied are you with general maintenance of the building? |
| Overall satisfaction | Satisfaction with workspace | All things considered, how satisfied are you with your personal workspace? |

The database also contains metadata describing technical aspects of the surveyed buildings, but not directly specifying the building's ventilation system. It does, however, contain information about HVAC systems, window air-conditioners, use of natural ventilation, and presence of operable windows, which allowed us to infer the type of ventilation system in each building. Based on these inferences the survey dataset was sorted into three types of building ventilation system: Air-Conditioned (AC), Mixed-Mode (MM), and Naturally-Ventilated (NV) building groups. Samples with missing values on these metadata fields were excluded from our analysis, hence a total of 22,518 samples were retained for our analysis. In order to obtain some indication of the degree of Personal Environmental Control (PEC) between different building types, subjects with the various personal climate control methods were cross-tabulated with building ventilation type (Table 2). An overwhelming majority of subjects in AC buildings (76.2%) depended on centralized air-conditioning systems with no possible means of PEC. In contrast, 80.7% of NV building subjects and 68.3% of MM building subjects were provided with PEC. Regardless of the ventilation system, about one third of occupants (34.5%) in this study had at least one mechanism to control their indoor climate, and subjects who had access to both operable windows and individual HVAC control amounted to only 1.4% of the total sample.

**Table 2. Cross-tabulation of subject samples by building ventilation type and personal environmental control**

| Building ventilation type | | Personal Environmental Control (PEC) method | | | | Total |
| --- | --- | --- | --- | --- | --- | --- |
| | | Operable window & individual HVAC control | Operable window | Individual HVAC control | No control | |
| AC | Count | 0 | 0 | 4,105 | 13,142 | 17,247 |
| | % | 0% | 0% | 23.8% | 76.2% | 100.0% |
| NV | Count | 0 | 397 | 0 | 95 | 492 |
| | % | 0% | 80.7% | 0% | 19.3% | 100.0% |
| MM | Count | 307 | 2,248 | 710 | 1,514 | 4,779 |
| | % | 6.4% | 47.0% | 14.9% | 31.7% | 100.0% |
| Total | Count | 307 | 2,645 | 4,815 | 14,751 | 22,518 |
| | % | 1.4% | 11.7% | 21.4% | 65.5% | 100.0% |

## 2.2 Identifying the impact of individual IEQ factors on overall satisfaction

In marketing research, a few analytical methods have been proposed to identify different categories of attributes (i.e. *Basic*, *Bonus* and *Proportional Factors*) and tested for their validity. Dummy variable regression is regarded as a reliable, valid and practical strategy that properly accounts for the nonlinear relationships between attribute-level performance and overall satisfaction [8,9]. Consequently it became the most commonly used analytical approach in studies of the asymmetric impact of different attributes on overall satisfaction (e.g. [10-12]). Thus, in our analysis, multiple regression with dummy variables was used to estimate the strength of each IEQ factor's impact on occupant overall workspace satisfaction under two circumstances; when the IEQ factor is deemed satisfactory by occupants, and when it isn't. This is based on the concept that the impact of IEQ factors on occupants' overall satisfaction with the workspace differs, depending on each IEQ factor's perceived performance level [6]. By comparing these two impacts 1) impacts on occupant overall satisfaction when the IEQ factor is performing satisfactorily (*positive impact*), and 2) when the IEQ factor is performing *un*satisfactorily (*negative impact*), we can categorize IEQ factors into the *Basic*, *Bonus* and *Proportional* categories defined in  Kano's satisfaction model. If the negative estimate is *greater* and *significantly different* from the positive estimate, then this IEQ factor is classified as a *Basic Factor*. On the other hand, if the positive estimate is *greater* and *significantly different* from the negative estimate, then this IEQ factor falls into the *Bonus Factor* category. Finally, if negative and positive estimates are not significantly different, then this IEQ factor is defined as a *Proportional Factor*. This analysis was conducted on three sub-samples of building occupants within the CBE's POE database; occupants of AC buildings, MM buildings and NV buildings separately.

In order to estimate the differential significance of IEQ factors in association with their perceived performance level, survey samples were divided into three groups using dummy coding (coded 0 or 1); a) those who were highly **satisfied** with the IEQ factor in question (subjects who rated their satisfaction at the top two levels i.e. +3 and +2), and b) occupants who were highly **dissatisfied** with the IEQ factor (subjects who rated their satisfaction at the lowest 2 levels i.e. -3 and -2), and c) those occupants who were indifferent to the IEQ factor (subjects who rated their satisfaction level in the middle of the scale i.e. -1, 0, and +1).  This third group is referred to as the **reference** group. The main reason for binning samples into three sub-groups (i.e. **satisfied**, **dissatisfied** and **reference**) lies in the uncertainty that the 7-point scale of satisfaction has the property of equal psychological intervals. For example, it is not verified that the psychological distance from a satisfaction vote of +2 to +1 is the same as the psychological distance from +1 to 0.

Therefore we decided to simplify the 7-point scale responses by binning into three groups. The logic behind this binning is directly comparable to that used by Fanger [13] in his mapping from a 7-point scale of thermal sensation onto a thermal satisfaction/*dis*satisfaction bifurcation. He defined *dis*satisfied (the "D" in PPD) as those who vote -2 or -3, +2 or +3, based on the evidence from Gagge et al. [14] – *"real discomfort is first expressed by those voting higher than +2 or lower than -2"*.

Then multiple regression analysis was conducted with overall workspace satisfaction as the dependent variable, and the other 15 IEQ factors as independent dummy variables. Therefore, as defined in the equation (1), the regression analysis produce two coefficients for each of the IEQ factors: one for 'satisfied group' to measure the impact when performance of the IEQ factor is perceived as performing well, and the other for the '*dis*satisfied group' to measure the impact when performance of the IEQ factor is rated as poor.

$$OS = b_0 + b_{1.factor1}X_{1.factor1} + b_{2.factor1}X_{2.factor1} + \ldots + b_{1.factor15}X_{1.factor15} + b_{2factor15}X_{2.factor15} \qquad (1)$$

$OS$: occupants' **O**verall **S**atisfaction score with workspace

$b_0$: average of overall satisfaction score of reference groups

$X_1$: dummy value for satisfied group of IEQ factors

$X_2$: dummy value for *dis*satisfied group of IEQ factors

$b_1$: regression coefficient for satisfied group (impact on overall satisfaction when performance on individual IEQ factor is deemed satisfactory)

$b_2$: regression coefficient for *dis*satisfied group (impact on overall satisfaction when performance on individual IEQ factor is deemed *un*satisfactory)

From the equation (1), the absolute value of the regression coefficient is interpreted as the strength of each IEQ factor's impact on occupant overall satisfaction, with positive coefficients contributing to increased overall satisfaction (positive impact), and vice versa for negative coefficients. Therefore comparison of $b_1$ and $b_2$ on each IEQ factor can be used as a basis of identifying *Basic*, *Bonus* and *Proportional Factors*. For example, if the absolute value of $b_1$ for IEQ factor *x* outweighs that of $b_2$ then IEQ factor *x* has a stronger impact on overall workspace satisfaction when occupants are satisfied with the performance on that IEQ factor, thus factor *x* is categorized as a *Bonus Factor*. Conversely, if the absolute value of $b_2$ on IEQ factor *y* outweighs that of $b_1$, then factor *y* is grouped into the *Basic Factor* category. Finally, if the two coefficients for IEQ factor *z* have broadly the same absolute value, which means that both negative and positive impacts are approximately equal, then factor *z* is defined as a *Proportional Factor*. The procedure for the analysis is illustrated in Fig. 2.
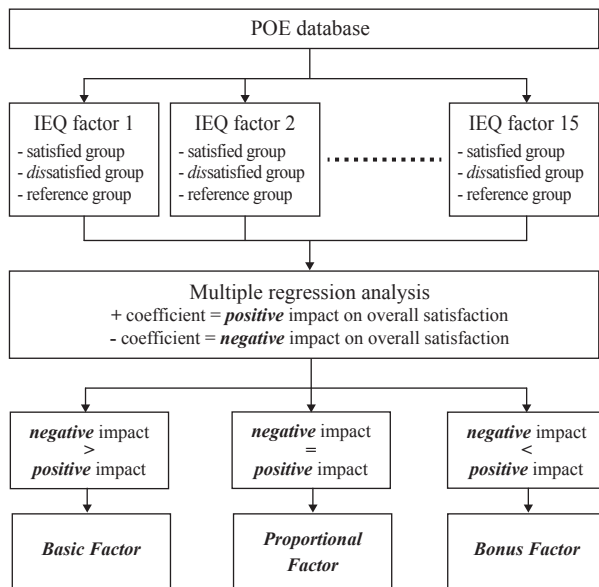
**Fig. 2. Schematic representation of the methodology used to categorize 15 IEQ factors into *Basic*, *Proportional* and *Bonus* groups**
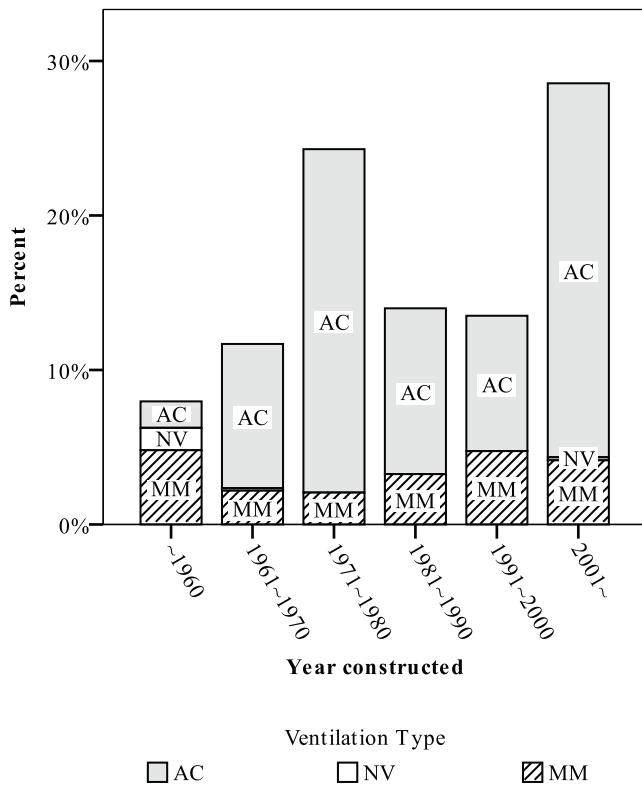
# 3. Results

## 3.1 Mean satisfaction level with IEQ factors

Fig. 3 illustrates the mean satisfaction ratings for the 15 IEQ factors plus the overall workspace, by occupants in AC, MM and NV buildings. All three types of building registered positive overall satisfaction with workspace, but MM and NV buildings were rated significantly higher than AC buildings ($p<0.05$). Occupants of AC, MM and NV buildings were all close to neutral on the satisfaction/*dis*satisfaction scale for 'temperature', but MM building occupants were more satisfied with 'temperature' than their counterparts in AC buildings. MM buildings consistently achieved higher satisfaction ratings than AC buildings on most of the 15 IEQ factors. On the one hand NV buildings achieved the highest mean satisfaction rating for some IEQ factors such as 'amount of light', 'noise level', 'sound privacy', 'amount of space', 'visual privacy' and 'ease of interaction', on the other hand they were rated considerably lower on fit-out, cleanliness and maintenance issues (the six right-most IEQ factors in Fig. 3). Building age possibly contributed to low satisfaction scores on these IEQ factors. The majority of NV building occupants included in this analysis were in buildings constructed before 1960 (Fig. 4), whereas the sample of AC and MM buildings were spread more evenly across the time-period. So the furnishings may be perceived to be old-fashioned and fit-out materials could be deemed less clean in the older NV building stock.
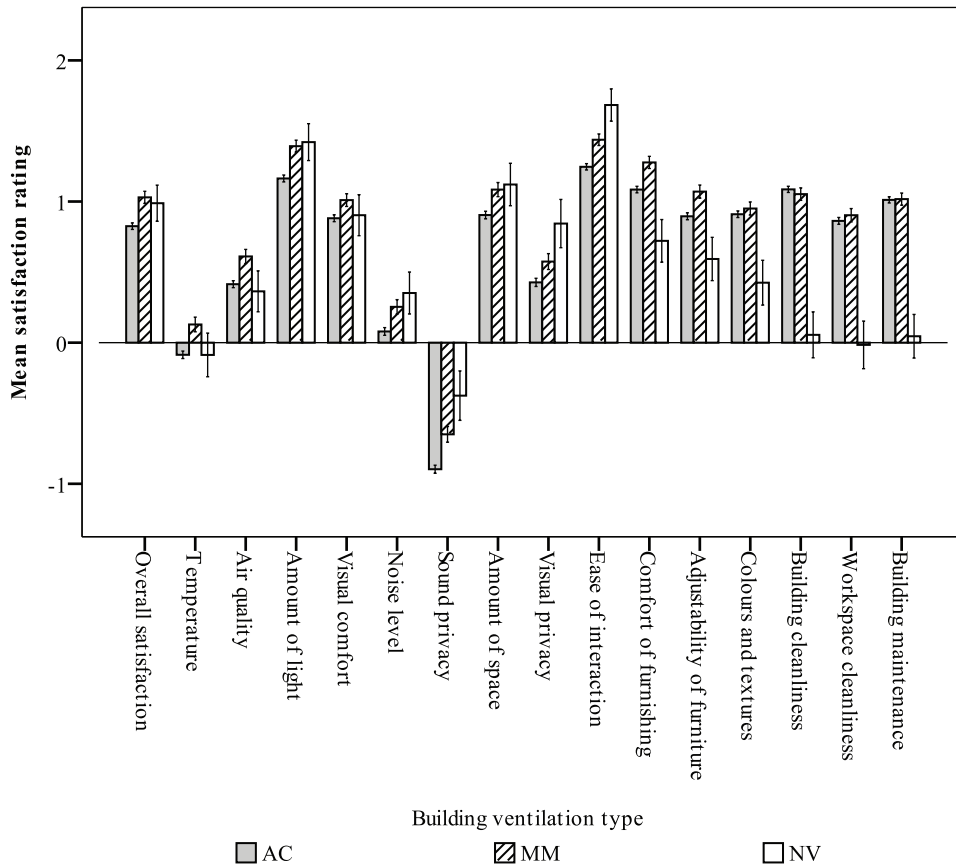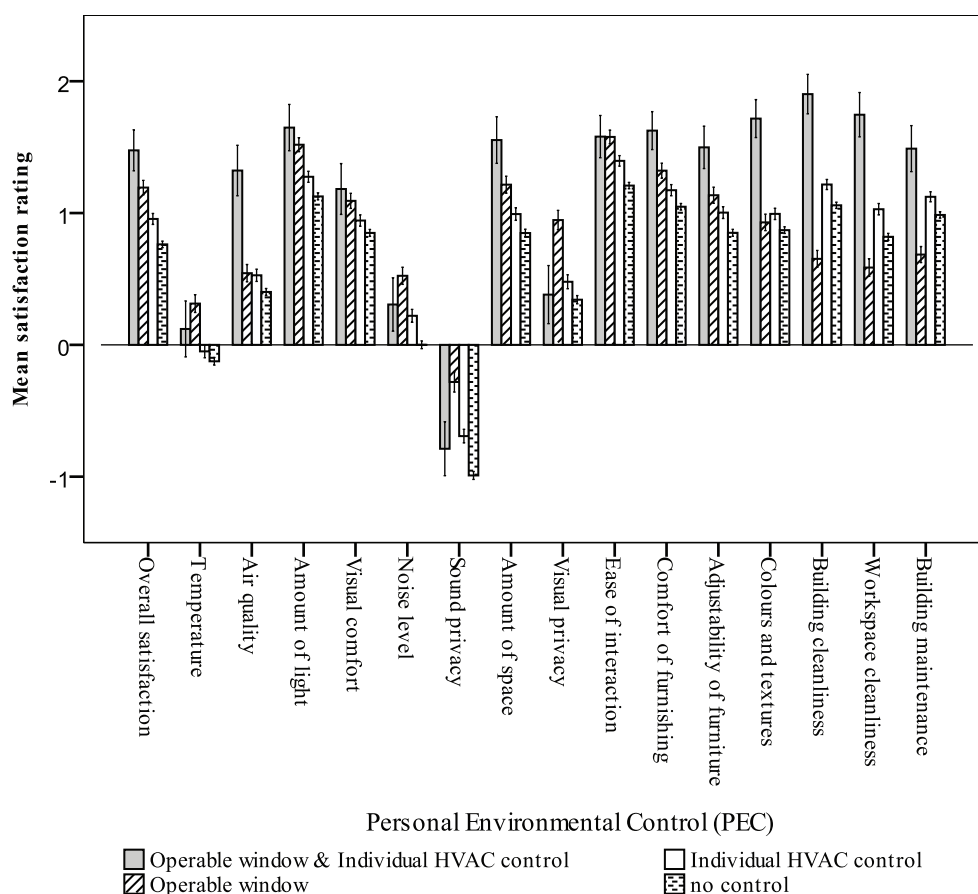
**Fig. 3.** Mean satisfaction rating (-3 = *'very dissatisfied'*, through 0 = *'neutral'* to 3 = *'very satisfied'*) for overall satisfaction and various IEQ factors by building ventilation types (Error bars represent 95% confidence interval)



**Fig. 4. Percentage of AC/NV/MM samples broken down by building completion year**

*Kim J, de Dear R. 2012. Impact of different building ventilation modes on occupant expectations of the main IEQ factors. Building and Environment. doi:10.1016/j.buildenv.2012.05.003*

Mean satisfaction scores by subjects with different means of personal environmental control are described in Fig. 5. Generally, occupants having access to both operable windows and HVAC controls are the most satisfied with their workspace environment ($p<0.05$), followed by those with access to operable windows ($p<0.05$), then individual HVAC controls ($p<0.05$), and last, those with no access to personal environmental controls at all ($p<0.05$). Interestingly, none of the personal environmental control groups rated their thermal environment very highly (satisfaction ratings were all close to *neutral* and not significantly different between groups). Although occupants with access to both HVAC and operable windows had highest level of satisfaction with air quality, space, furniture, cleanliness and maintenance, the total size of this subgroup of occupants in the total sample was small (1.4% in Table 2).

Comparing occupants with access to operable windows with those who had individual HVAC controls, the former group seems to have the higher overall workspace satisfaction levels, as well as temperature, amount of light, visual comfort, noise level, sound privacy, amount of space, visual privacy, ease of interaction, comfort and adjustability of furnishings. The only IEQ factors on which satisfactions ratings for the operable window group were lower than the other control groups were related to cleanliness and maintenance issues (the three right-most IEQ factors), possibly due to ingress of external dirt and pollution.



**Fig. 5. Mean satisfaction rating (-3 = *'very dissatisfied'*, through 0 = *'neutral'* to 3 = *'very satisfied'*) for overall satisfaction and various IEQ factors by personal environmental control methods (Error bars represent 95% confidence interval)**

## 3.2 Classifying IEQ factors as *Basic, Bonus* and *Proportional*

The primary research question of this paper is whether occupants of buildings with the different ventilation type (AC, MM, NV) have different IEQ priorities in relation to overall workspace satisfaction. The results of the separate regression analyses conducted on the three different groups of occupant (AC, MM, NV) provided useable predictive capability by explaining 61~65% of variance in occupant overall satisfaction (AC building occupants $R^2$=0.63, MM building occupants $R^2$=0.65, and NV building occupants $R^2$=0.61). Also, multi-collinearity effects between predictors were investigated and independence of predictors was established. Two regression coefficients per IEQ factor were derived from the procedure described in section 2.2; one to estimate the IEQ factor's impact on overall satisfaction when performance on that IEQ factor was deemed satisfactory, and the other when performance of the IEQ factor was deemed *un*satisfactory.

**Table 3. Differential impact of IEQ factors on overall workspace satisfaction for occupants who were satisfied with the IEQ factor compared, with those who were *dis*satisfied**

| | IEQ factor | Occupants of AC buildings | | | | Occupants of MM buildings | | | | Occupants of NV buildings | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Regression coefficients | | Sig. difference | Category | Regression coefficients | | Sig. difference | Category | Regression coefficients | | Sig. difference | Category |
| | | Satisfied group | *Dis*satisfied group | | | Satisfied group | *Dis*satisfied group | | | Satisfied group | *Dis*satisfied group | | |
| 1 | Temperature | 0.11* (0.07; 0.15) | -0.22* (-0.25; -0.18) | YES | *Basic* | 0.11* (0.04; 0.17) | -0.22* (-0.29; -0.15) | NO | Prop. | 0.31* (0.09; 0.54) | -0.12$^{NS}$ (-0.33; 0.09) | YES | **Bonus** |
| 2 | Air quality | 0.17* (0.13; 0.21) | -0.15* (-0.20; -0.11) | NO | Prop. | 0.13* (0.06; 0.19) | -0.22* (-0.31; -0.14) | NO | Prop. | 0.15$^{NS}$ (-0.09; 0.38) | -0.04$^{NS}$ (-0.31; 0.24) | - | - |
| 3 | Amount of light | 0.16* (0.12; 0.20) | -0.18* (-0.24; -0.12) | NO | Prop. | 0.24* (0.16; 0.31) | -0.13^ (-0.27; 0.00) | NO | Prop. | 0.13$^{NS}$ (-0.12; 0.37) | -0.08$^{NS}$ (-0.55; 0.39) | - | - |
| 4 | Visual comfort | 0.10* (0.06; 0.14) | -0.18* (-0.24; -0.12) | NO | Prop. | 0.04$^{NS}$ (-0.04; 0.11) | -0.10$^{NS}$ (-0.21; 0.01) | - | - | 0.05$^{NS}$ (-0.19; 0.29) | -0.40^ (-0.77; -0.03) | YES | *Basic* |
| 5 | Noise level | 0.21* (0.17; 0.25) | -0.42* (-0.46; -0.38) | YES | *Basic* | 0.16* (0.09; 0.23) | -0.38* (-0.45; -0.30) | YES | *Basic* | 0.24^ (0.02; 0.45) | -0.21$^{NS}$ (-0.46; 0.04) | YES | **Bonus** |
| 6 | Sound privacy | 0.13* (0.08; 0.18) | -0.14* (-0.18; -0.10) | NO | Prop. | 0.21* (0.13; 0.29) | -0.22* (-0.29; -0.16) | NO | Prop. | 0.27^ (0.02; 0.51) | -0.34* (-0.56; -0.11) | NO | Prop. |
| 7 | Amount of space | 0.42* (0.39; 0.46) | -0.82* (-0.87; -0.77) | YES | *Basic* | 0.44* (0.37; 0.50) | -0.81* (-0.90; -0.71) | YES | *Basic* | 0.34* (0.13; 0.55) | -0.91* (-1.24; -0.57) | YES | *Basic* |
| 8 | Visual privacy | 0.18* (0.15; 0.22) | -0.42* (-0.47; -0.38) | YES | *Basic* | 0.21* (0.14; 0.28) | -0.40* (-0.48; -0.32) | YES | *Basic* | 0.10$^{NS}$ (-0.12; 0.32) | -0.31^ (-0.59; -0.02) | YES | *Basic* |
| 9 | Ease of interaction | 0.19* (0.16; 0.22) | -0.24* (-0.30; -0.18) | NO | Prop. | 0.28* (0.22; 0.34) | -0.22* (-0.34; -0.09) | NO | Prop. | 0.46* (0.26; 0.66) | -0.05$^{NS}$ (-0.66; 0.56) | YES | **Bonus** |
| 10 | Comfort of furnishing | 0.20* (0.15; 0.24) | -0.21* (-0.27; -0.14) | NO | Prop. | 0.08^ (0.00; 0.17) | -0.26* (-0.40; -0.13) | NO | Prop. | 0.15$^{NS}$ (-0.10; 0.40) | -0.35$^{NS}$ (-0.70; 0.01) | - | - |
| 11 | Adjustability of furniture | 0.10* (0.05; 0.14) | -0.18* (-0.24; -0.12) | NO | Prop. | 0.09^ (0.01; 0.17) | -0.19* (-0.31; -0.07) | NO | Prop. | 0.01$^{NS}$ (-0.25; 0.26) | 0.01$^{NS}$ (-0.33; 0.35) | - | - |
| 12 | Colours & textures | 0.16* (0.12; 0.19) | -0.27* (-0.32; -0.21) | YES | *Basic* | 0.17* (0.10; 0.23) | -0.34* (-0.44; -0.24) | YES | *Basic* | 0.06$^{NS}$ (-0.16; 0.28) | -0.04$^{NS}$ (-0.30; 0.23) | - | - |
| 13 | Building cleanliness | 0.09* (0.04; 0.13) | -0.06$^{NS}$ (-0.13; 0.02) | YES | **Bonus** | 0.07$^{NS}$ (-0.01; 0.16) | -0.05$^{NS}$ (-0.18; 0.07) | - | - | 0.62* (0.26; 0.97) | -0.20$^{NS}$ (-0.49; 0.08) | YES | **Bonus** |
| 14 | Workspace cleanliness | 0.05^ (0.01; 0.09) | -0.07^ (-0.12; -0.01) | NO | Prop. | 0.03$^{NS}$ (-0.05; 0.10) | -0.03$^{NS}$ (-0.13; 0.07) | - | - | -0.28$^{NS}$ (-0.59; 0.02) | -0.19$^{NS}$ (-0.44; 0.07) | - | - |
| 15 | Building maintenance | 0.14* (0.09; 0.18) | -0.13* (-0.20; -0.06) | NO | Prop. | 0.18* (0.10; 0.26) | -0.06$^{NS}$ (-0.18; 0.06) | YES | **Bonus** | -0.02$^{NS}$ (-0.34; 0.30) | -0.27^ (-0.53; -0.01) | YES | *Basic* |

(1) $R^2$=0.63, constant=0.41 (AC building); $R^2$=0.65, constant=0.45 (MM building); $R^2$=0.61, constant=0.53 (NV building)
(2) Significance level of regression coefficients: *$P$<0.01, ^$P$<0.05, NS=Not Significant
(3) Lower and upper bound of Confidence Intervals (95%) are in parenthesis
(4) Sig. difference: significant difference in the magnitude of the impact ($P$<0.05)
(5) *Basic*=Basic Factor; Prop.=Proportional Factor; **Bonus**=Bonus Factor

Table 3 summarises the results from the dummy variable regression analysis. Regression coefficients and their 95% confidence intervals for the 15 IEQ factors were established separately for occupants of AC, MM and NV buildings. Regression coefficients for the 'satisfied group' represent the positive impact of each IEQ factor, increasing overall workspace satisfaction, while regression coefficients for '*dis*satisfied group' represent the negative impact, decreasing overall workspace satisfaction. The absolute value of the coefficients represents the magnitude of impact, thus comparison of both positive and negative coefficients enables classification of IEQ factors as either *Basic, Bonus* or *Proportional*. For example, in AC buildings, when thermal conditions ('temperature') in a building are satisfactory,

their impact on overall satisfaction is relatively low (regression coefficient = +0.11: i.e. increasing the overall satisfaction score by 0.11). However when the AC buildings' occupants are *dis*satisfied with their buildings' thermal performance, the magnitude of the impact of 'temperature' doubled (regression coefficient = -0.22: i.e. decreasing the overall satisfaction score by 0.22). Thus, in AC buildings, the impact of 'temperature' on occupant overall satisfaction is bigger when the thermal performance of the building is perceived to be poor. Moreover the absolute magnitude of the impact is significantly different between satisfied and *dis*satisfied groups (i.e. the 95% confidence intervals of the positive and negative regression coefficients don't overlap). Therefore 'temperature' falls into the *Basic Factor* category in Kano's satisfaction model, so it can be regarded as a minimum requirement (expectation) for AC buildings, having a minor impact when performance meets expectations, but prompting significant overall displeasure when failing to meet those expectations. In MM buildings, the regression coefficients were the same with those of AC buildings, but the difference in the magnitude between positive and negative impacts was not statistically significant (i.e. the 95% confidence intervals of the positive and negative regression coefficients overlap). Therefore 'temperature' is classified as a *Proportional Factor* in MM buildings, exerting its impact on overall workspace satisfaction in approximately equal magnitude for both positive and negative performance. When a building's thermal condition is perceived as comfortable there is a positive improvement in the occupants' overall satisfaction with their workspace. When thermal *dis*comfort is experienced in an MM building, there is an equal but opposite effect on overall satisfaction rating. In contrast, 'temperature' in NV buildings had a strong positive impact on overall satisfaction (regression coefficient = +0.31), approximately three times bigger than that observed in AC and MM buildings. Furthermore, the negative impact of 'temperature' on occupant overall satisfaction was statistically insignificant in NV buildings. Therefore 'temperature' fits Kano's definition of *Bonus Factor* in NV buildings – being forgiven [1] when perceived to be underperforming, but pleasantly surprising when performance exceeds expectations.

Applying the same logic, the remaining IEQ factors were categorized as *Basic*, *Bonus* or *Proportional*. Some of the IEQ factors failed to achieve statistically significant results in MM and NV building subsamples due to the relatively small sample sizes of these buildings in CBE's database. The NV group showed the greatest number of *Bonus Factors*, but the AC and MM building sample only had one *Bonus Factor*. Excluding those IEQ factors that couldn't be classified, three IEQ factors were consistently classified regardless of building ventilation types, namely 'sound privacy' (*Proportional*), 'amount of space' (*Basic*) and 'visual privacy' (*Basic*). Apparently commercial office building occupants expect a certain level of quality in terms of privacy and proxemics, irrespective of their building's ventilation type. 'Noise level' was regarded as basic requirements (i.e. *Basic Factors*) in AC and MM buildings, but it was classified as *Bonus Factors* in the NV building sample. Building cleanliness and maintenance issues only had minor effects on overall satisfaction compared to other IEQ factors, except 'building cleanliness' in NV group, which had the strongest positive impact on overall satisfaction (regression coefficient =+0.62). Ease of interaction with co-workers also had a strong positive impact (*Bonus Factor*) for occupants in NV buildings with a regression coefficient=+0.42, but the causal linkages leading to this result remain unclear due to a lack of building meta-data such as office density, layout and job characteristics in the CBE database that was supplied.

Fig. 6 illustrates both positive and negative impacts of the 15 individual IEQ factors on overall satisfaction in AC, MM and NV buildings respectively, using regression coefficients in Table 3 as the index. The upper (un-shaded) bar represents magnitude of positive impact and the lower part (shaded) represents negative impacts. Thus the relative

magnitudes of both positive and negative impacts on overall satisfaction resulting from each IEQ factors can be gleaned from this figure. Some IEQ factors had a predominantly negative impact while others had mainly positive impacts, and yet others had approximately equal impacts on both directions. The bar charts in Fig.6 indicates different patterns for different building ventilation types. While AC and MM building groups showed broadly similar patterns, occupants in NV building gave different results for several IEQ factors as explained above.
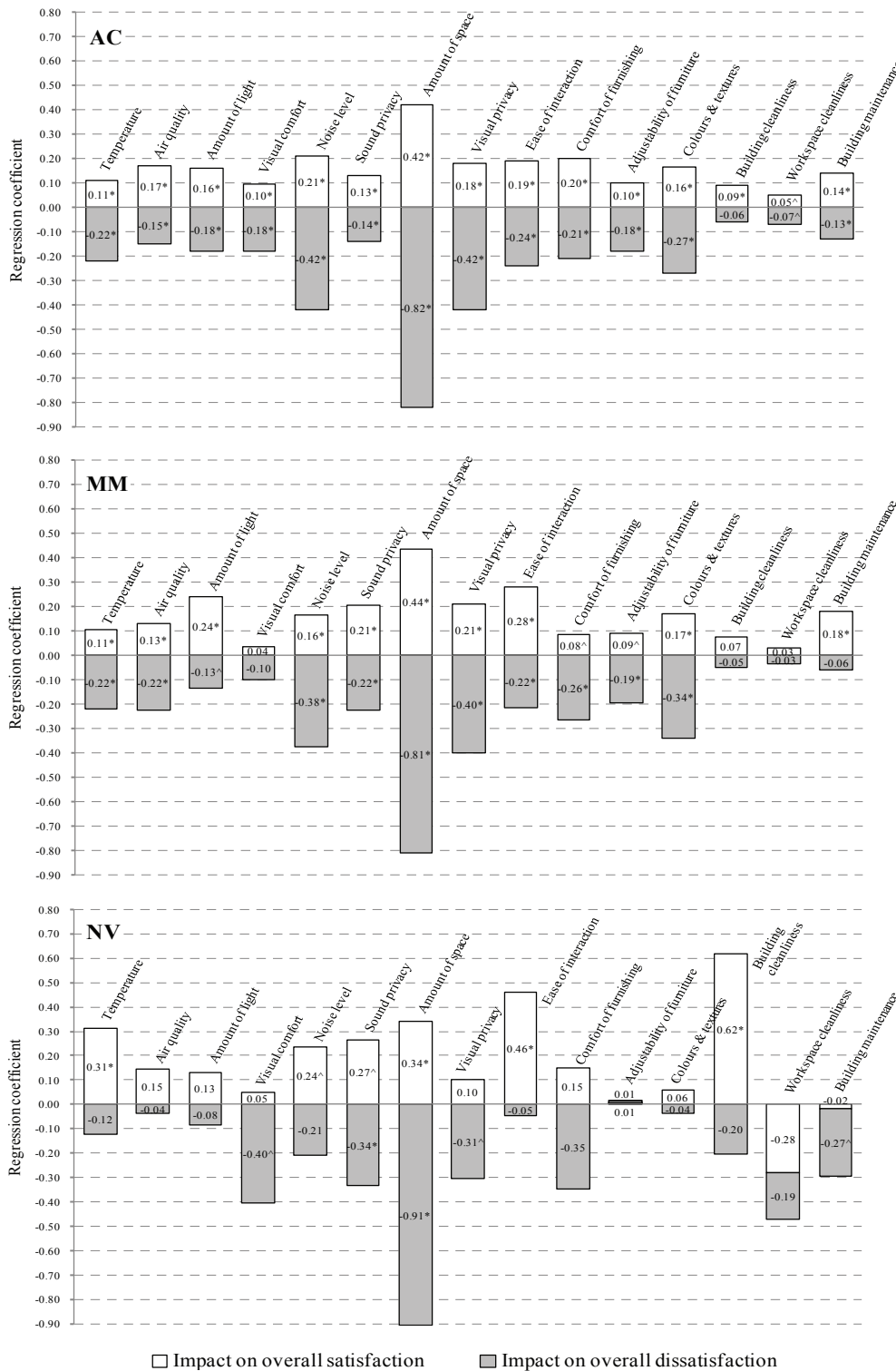


**Fig. 6. Positive (unshaded bar) / negative (shaded bar) impacts of IEQ factors on overall workspace satisfaction of occupants in AC, MM, and NV buildings. The values inside each bar are regression coefficients (\*=P<0.01, ^=P<0.05).**

# 4. Discussion

## 4.1 Occupants' different expectations for thermal comfort

In an earlier literature review on the relative importance of IEQ factors to overall satisfaction [15] we noted that most researchers ranked thermal comfort as the most important IEQ factor. But in the current analysis we found that thermal issues exerted their impact on overall satisfaction in different ways, depending on the type ventilation approach of the building. In Table 3, we noticed that 'temperature' was the only main IEQ factor classed into three different Kano's categories according to the ventilation type (except 'building maintenance'); 'Temperature' was classified as a *Bonus Factor* in NV buildings, but a *Proportional Factor* in MM buildings, and *Basic Factor* in AC buildings. In other words, provision of thermal comfort is apparently a minimum requirement for people working in centrally air-conditioned buildings. When the thermal performance of these buildings is deemed to be *un*satisfactory, occupants' overall workplace satisfaction decreases significantly. In short, thermal performance inside AC buildings is likely to be noticed only when it fails to meet expectations. However, occupants of NV buildings apparently have relatively modest expectations of the thermal environment inside their buildings, and when temperature performance is good, exceeding their expectations such that their satisfaction generalises to overall workspace IEQ. Conversely, thermal *dis*comfort in NV buildings doesn't necessarily translate to overall *dis*satisfaction with the building because it has already been factored into the occupant's expectations. Finally, 'temperature' effects on overall satisfaction in MM buildings seem to have characteristics that were identified in both AC and NV buildings. Occupants' overall workspace satisfaction level changes are commensurate with their perception of the building's thermal performance. In other words, when a building provides a comfortable thermal environment, occupants will be satisfied and when the building is failing to deliver thermal comfort occupants will be *dis*satisfied with their overall workspace.

This hypothesis for differential expectations of indoor thermal quality can be inferred from previous IEQ research literature: De Dear and Brager [16] argued that occupants in air-conditioned spaces develop high expectations for thermal uniformity in their indoor climate, becoming quite critical if thermal conditions deviate even slightly from their familiar range. Occupants in naturally-ventilated buildings, on the other hand, are more closely connected to the outdoor climate by operable windows, hence become used to thermal variety in their indoor environments. Possibly the expectation levels developed by occupants' different experiences in buildings with different ventilation systems lead to their differential categorization of thermal performance into *Basic Factor* (AC buildings), *Proportional Factor* (MM buildings) and *Bonus Factor* (NV buildings). This reinforces Brown and Coles' [17] conjecture that expectations play an important role in shaping occupant comfort and indoor environmental behaviour. Perhaps people working in naturally-ventilated spaces pay particular attention to local weather conditions and are adept at predicting their building's thermal response – so they are not surprised by cool or warm indoor temperature deviations, and therefore are more forgiving as a result. In air-conditioned spaces, on the other hand, where people are isolated from the outdoor environment, occupants expect their buildings to provide consistent thermal environmental conditions regardless of outdoor weather conditions. Then when *dis*comfort occurs, occupants are taken by surprise and are reluctant to adapt themselves to accommodate thermal fluctuations. Our analysis in this paper implicitly supports Baker and Standevens' [18] speculation that thermal *dis*satisfaction doesn't necessarily result from non-neutral thermal condition, but rather when the thermal stimulus exceeds the limits of adaptive opportunity available to the occupants at that point in time. When the cause of stimulus (like outdoor weather) is understood and good adaptive opportunity is provided,

occupants' comfort zone is extended. To sum up, our analysis in this paper provides rare empirical evidence in support of a widespread belief that adaptive opportunity in the built environment influences the way occupants perceive IEQ. In this analysis, buildings with the highest degree of adaptive opportunity, as assessed by personal environmental control items on the CBE questionnaire, were the naturally ventilated buildings, followed by mixed mode buildings, and then air conditioned buildings (see Table 2).

The analysis in this paper points to the possibility that occupants' expected or presumed levels of IEQ performance within a specific building might play a role not only in their reactions to thermal environment, but also the acoustic conditions. The regression analysis classified 'noise level' as a *Basic Factor* in AC and MM buildings, but as a *Bonus Factor* in NV buildings (Table 3). Perhaps this observation indicates that occupants of NV buildings are less sensitive to externally generated noise because they accept it as a necessary trade-off with thermal comfort in the operable window scenario.

## 4.2 Adaptive opportunity influencing occupants' satisfaction with various IEQ factors

Previous empirical studies usually link adaptive opportunity with occupant thermal comfort (e.g. [19,20]), but the connection between thermal adaptation and occupant satisfaction with other, non-thermal IEQ aspects is not common. Baker and Standeven [18] suspected that restricted adaptive opportunity narrows the comfort zone and eventually heightens occupant sensitivity to other stimuli. In Fig. 5, we noticed that occupants with ample thermal adaptive opportunities (i.e. access to operable windows *and* HVAC controls) also expressed high levels of satisfaction with many of the other IEQ factors as well, compared to their counterparts in buildings with restricted thermal adaptive opportunities. Not wishing to overgeneralise this result, but it hints that adaptive opportunity is a generic attribute of buildings that influences not just thermal IEQ but other indoor environmental dimensions as well. This question deserves further investigation in future.

## 4.3 The effect of perceived control on occupants' attitudes and expectations

The psychology literature indicates that perceived control is a significant determinant of how we respond to aversive stimuli; our response to an event will be different if we feel that we were responsible for causing it, or whether it was the consequence of external forces beyond our control (e.g. [21,22]). The 'locus of control' theory in psychology, or perceived control over the indoor environment described as *environmental empowerment* by Vischer [23], suggests that a building occupant's attitude toward, and expectations of their building's thermal performance could be affected by where they perceive the 'locus of thermal control' to lie; internal versus external. In naturally-ventilated buildings occupants are fully responsible for achieving their own thermal comfort – *internal* locus of control. For example, people in NV buildings respond to a given thermal condition by availing themselves of adaptive opportunities such as operable windows, adjusting clothing insulation or drinking cold/hot beverages. Hence when they experience thermal *dis*comfort, they tend to regard it as a consequence of their own response toward the thermal environment rather than the thermal environment provided by the building; we found thermal *dis*comfort in NV buildings to be not significantly associated with negative overall workspace satisfaction (Table 3). In contrast, in centrally air-conditioned buildings occupants seem more likely to attribute thermal *dis*comfort to their building's poor thermal performance rather than their own maladaptation to those conditions – *external* locus of control. They interpret their personal thermal experience as a consequence of external factors beyond their control (e.g. facilities manager) instead of ameliorating the situation through adaptive opportunities at their disposal. Our finding that thermal *dis*comfort was

significantly associated with negative overall workspace satisfaction in AC buildings (Table 3) is consistent with this interpretation.

## 4.4 Limitations of the study and suggestions for further research

Through a statistical analysis of CBE's post-occupancy survey database this paper identified differences in the impacts of indoor thermal environment on overall workspace satisfaction, depending on the building's mode of ventilation (AC, MM and NV buildings). We couched our explanation of these differences in terms of adaptive opportunity; with NV buildings having the highest degree of adaptive opportunity, AC buildings the least, and MM buildings somewhere in the middle. However, the meta-data in the CBE's database contains limited information regarding individual HVAC control and operable windows, so how effectively those features were in each sample building remains moot. Therefore the effectiveness or usability of personal environmental control in each building could not be reflected in our classification of buildings. When classifying buildings by ventilation type we inferred that presence of air-conditioning system and operable window corresponded to an MM building. But it is also conceivable that some buildings operating exclusively in central air-conditioning mode were classified as MM building because of the presence of operable windows, regardless of whether or not those windows were ever used for ventilation and thermal comfort. Anecdotal evidence from operators of many of Australia's recent MM buildings indicates they often revert to full-time AC mode a year or two post occupancy, for reasons that remain unclear at this stage. Others have noted that it is not unusual to find AC buildings with disused operable windows [24], and so misclassification of buildings between MM and AC categories in this analysis cannot be ruled out.

Another limitation is that the type of data available to this analysis was confined to just the subjective ratings. There were no instrumental observations of objective physical conditions to accompany the subjective POE data, so it remains unknown how those buildings in the database were *actually* performing. So while our analysis demonstrated that occupants of AC, MM and NV buildings all had different perceptions of their buildings' indoor environmental conditions, we cannot definitively say that this was the result of differences in *actual* physical conditions provided by the buildings. We acknowledge this as the main limitation of this study, therefore more detailed information about actual performance of each buildings and effectiveness or usability of personal control method in MM and NV buildings are crucial to make the result or discussions more concrete. This represents a fundamental limitation of contemporary POE techniques.

## 5. Conclusion

This study was based on the hypothesis that three types of relationship between occupant overall satisfaction and the performance of IEQ criteria (i.e. *Basic*, *Bonus* and *Proportional Factor* defined in Kano's model) can differ between occupant groups, depending on what people expect from their building. And the patterns of those relationships differed between AC, MM and NV occupant groups. That is, people working in buildings with different types of ventilation have different requirements and respond in different ways to various IEQ issues, depending on their expectation levels. In particular, people showed noticeable differences in attitude towards their buildings' thermal performance. Those in air-conditioned buildings seemed to have higher expectations of thermal performance, and when a building failed to meet those expectations, occupants were highly critical of their building overall. In contrast, occupants of naturally-ventilated buildings tend to accept, or at least forgive, less-than-ideal thermal performance

because their evaluation of the overall performance of the building was not adversely affected. Also some other different patterns of occupants' responses toward various IEQ factors (such as 'noise level', 'ease of interaction' and 'building cleanliness') were detected, but we had insufficient building meta-data in the CBE database to make any inferences. To conclude, contextual differences seem to have an influence on occupants' satisfaction with indoor environmental quality.

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