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Occupant satisfaction with the indoor environment in seven commercial buildings in Singapore

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Abstract

Understanding occupants' satisfaction with their environment is an important step to improve indoor environmental quality (IEQ). These satisfaction data are limited to Singaporean commercial buildings. We surveyed (N = 666) occupant satisfaction with 18 IEQ parameters in seven Green Mark certified air-conditioned commercial buildings in Singapore. About 78 % of the participants expressed satisfaction with their overall workspace environment. Occupants were most satisfied with flexibility of dress code (86 % satisfaction), electrical lighting (84 %) and cleanliness (82 %), and most dissatisfied with sound privacy (42 % dissatisfaction), personal control (32 %) and temperature (30 %). We found that satisfaction with cleanliness has the highest impact to overall workspace environment satisfaction. Our results suggest achieving high occupant satisfaction for some IEQ factors is harder than others, which suggests the premise of singular satisfaction rating (e.g., 80 %) that applies to all IEQ parameters may not be reliable and representative. We determined that the major contributors to thermal dissatisfaction were insufficient air movement and overcooled workspaces. Occupants in open plan office were unhappy with the noise produced by their nearby colleagues. We also found that several IEQ variables (odors, air movement, available space, overall privacy, sound privacy and temperature) which are not statistically significant to the overall workspace satisfaction on their own, but their impacts becomes substantial when these IEQ variables are merged into larger environmental factors (i.e., Perceived Air Quality, Acoustics, Layout and Thermal). These results can support the development of an IEQ benchmarks for commercial buildings in Singapore.

Keywords: Commercial buildings, Indoor Environmental Quality (IEQ), Occupants' satisfaction, Post-occupancy evaluation, Web-based survey

Graphical abstract



1. Introduction

Sustainable buildings should aim to achieve substantial energy savings and reduce greenhouse gases emission, while also providing good Indoor Environmental Quality (IEQ) that satisfies building occupants. IEQ affects occupants' health, comfort, well-being and productivity [1,2]. Conducting a post-occupancy evaluation (POE), with a widely adopted and reliable survey tool, could provide valuable information in understanding occupant satisfaction with the built environment, and identify areas in need of improvement.

The Centre for the Built Environment (CBE) at the University of California, Berkeley, has been developing and maintaining an effective and reliable occupant survey tool to gather occupant's satisfaction surveys for more than 20 years [3,4]. The latest version of the IEQ survey tool has been implemented in over 900 buildings, with over 90,000 individual occupant responses. The survey aims to collect occupant perceptions of and satisfaction with a space's IEQ as well as characteristics of the target building.

The CBE IEQ Occupant Survey database facilitates studies examining occupant satisfaction with the built environment across a large, diverse sample. For instance, responses within the CBE database have been used to compare occupant's satisfaction in LEED versus non-LEED certified buildings [5–7]; relationships between individual IEQ factors and overall workspace satisfaction [8,9]; comparison of acoustics and temperature satisfaction between radiant and all-air buildings [10]; and exploration of occupant satisfaction and self-estimated performance in relation to IEQ parameters in buildings [11]. Despite the large sample size and building type variety available in the CBE database, the buildings sampled are mainly located in the US.

About 43 % of the world's population is now housed in the tropics, and this figure will likely increase to >50 % by the year 2050 [12]. An increasing trend in the investment of research and development and scientific publication is observed in the tropics [12]. It is expected occupant satisfaction with the indoor built environment could be different in tropical climate countries due to different building design and construction practices, and occupant preferences, expectations, and cultural norms. For example, satisfaction with regards to the thermal environment could differ due to environmental adaptation [13,14].

Singapore is located at 1.3° N, 103.8° E and belongs to the tropical rainforest climate "Af" based on the Köppen Climate Classification [15]. Throughout the year, the climate in Singapore is warm and humid, with a daily mean outdoor air temperature of 26 – 29 °C and a daily mean relative humidity of 75 – 85 % [16]. In Singapore, a requirement for the Green Mark certification involves obtaining occupants' satisfaction with a building's environment via post-occupancy evaluation assessment. Green Mark is a rating system designed to evaluate a building's performance and environmental impact [17]. Green Mark recommends that a building achieves an occupant satisfaction level of at least 80 %. This 80% level is a macro indicator, and generally represents a substantial majority of people's decisions, similar to ASHRAE 62.1, ASHRAE 55 and ISO 7730 [18,19]- yet it is a precept, instead of a hard mathematical law. This target may be easy to achieve for some environmental parameters, but could be harder for others. One study examining IEQ satisfaction from 367 occupants in 14 buildings in Singapore showed that satisfaction with window view, personal control, temperature, air movement, daylight, visual comfort, visual privacy, air quality, noise level and sound privacy failed to achieve the 80 % level, even in Green Mark certified buildings [14]. In fact, occupants' perceived comfort and satisfaction with indoor environmental parameters could differ due to contextual and behavioural factors [20], and singular satisfaction ratings applying to all IEQ parameters may not be adequate.

Another important issue is to understand which parameters, or cluster of parameters, contribute the most to overall environmental satisfaction. Using the CBE database, Frontczak et al. found the most important parameters for workspaces satisfaction were satisfaction with amount of space, followed by noise level and visual privacy [8]. Working with the same database using a multiple regression approach, Kim and de Dear also found that amount of space, noise level and visual privacy affected overall satisfaction the most [9]. In the Cost-effective Open-Plan Environments (COPE) project in Canada, Veitch et al. found that satisfaction with workspaces' environment features can be reduced to three major factors, including "privacy/acoustics", "lighting" and "ventilation/temperature", and the satisfactions with these three factors and the overall environment were positively associated [21]. The Workplace Wellness Study surveyed 1601 employees in North America, suggested air quality (58 %) was the most highly-rated wellness factor in office, followed by comfortable lighting (50 %) and comfortable temperature (34 %) [22]. In Singapore, there could be different associations between IEQ parameters and overall environment satisfaction due to different contextual and behavioural characteristics found in the tropics. Through pinpointing which parameters comprise overall satisfaction, this information could help guide policymakers' decisions on which factors to focus guidelines towards design and operation practices. Understanding how overall satisfaction is achieved also helps building owners, operators, and employers to prioritize how to make decisions to maximize tenant satisfaction in the workspace when resources are limited.

In this study, we surveyed occupant satisfaction in seven commercial buildings in Singapore using a survey adapted from the CBE IEQ Occupant Survey. The objectives are (i) to study occupants' satisfaction level with different IEQ factors and verify which IEQ factors can achieve an 80% target occupant satisfaction; (ii) to understand the reason(s) that caused environmental dissatisfaction; and (iii) to identify which IEQ factors have higher impacts on occupant satisfaction with the overall workspace in Singapore's commercial buildings.

2. Methodology

2.1. Survey tool design

We modified the original CBE IEQ Occupant Survey [8] to be appropriate for building characteristics and operation in Singapore. The changes have been informed and acknowledged by CBE. In particular, we added questions on satisfaction with humidity and air movement because of the hot and humid climate characteristics in Singapore. Meanwhile, we removed satisfaction with general maintenance and ease of interaction from the original CBE survey, because our survey scope is within workspace, instead of the whole building (for maintenance), and we focused on the impact of environmental parameters to people, instead of workspace culture (for ease of interaction). We combined similar parameters in the CBE tool to reduce the number of questions in the survey. For example, we merged measurement of the comfort of furnishing and furniture adjustability in the original CBE survey with the satisfaction with furnishing. Similarly cleaning services and general cleanliness were combined with satisfaction with cleanliness. In contrast, some parameters in the original CBE survey tool were broken into more precise variables. For example, visual comfort was broken into satisfaction with daylight, view from window and glare; and similarly, air quality satisfaction was divided into satisfaction with odors and stuffiness.

Each satisfaction question is structured on a 7-point Likert scale and starts with: "How satisfied are you with the ..." followed by the environmental factors in question. As shown in Figure 1, the scale is ranged from "very satisfied" (+3) to "very dissatisfied" (-3) with a midpoint of "neither satisfied nor dissatisfied" (0). The survey assesses 18 parameters: temperature, humidity, air movement, flexibility of dress code, electrical lighting, natural

lighting, glare, views from windows, stuffiness, odours, noise level, sound privacy, cleanliness, available space, furnishings, level of personal control, overall privacy and overall environment. In this study, the dissatisfaction rate (D) and satisfaction rate (S) are estimated by Equations (1) and (2). The average satisfaction score in each IEQ category is calculated as the arithmetic mean of the responses.

$$\text{Dissatisfaction rate, } D (\%) = \frac{\text{Very dissatisfied count} + \text{Dissatisfied count} + \text{Somewhat dissatisfied count}}{\text{Total sample count}} \quad (1)$$

$$\text{Satisfaction rate, } S (\%) = \frac{\text{Very satisfied count} + \text{Satisfied count} + \text{Somewhat Satisfied count}}{\text{Total sample count}} \quad (2)$$

Further, if a “dissatisfied” response was recorded by the occupant, follow-up questions were asked to identify the source of dissatisfaction. The possible sources of dissatisfaction are categorized into four core environmental aspects in accordance with the original CBE survey tool classification, namely, thermal environment, air quality, lighting and sound. Within the same category, occupants can select more than one source of or reason for dissatisfaction. For example, within the thermal environment category, an occupant can be dissatisfied with the space being too hot and the air movement being too weak in workspace. In addition, an “others” option is provided for each category so that occupants can list any other source of dissatisfaction not included in the response set. The questionnaire also collects background information from respondents including sex, age group, hours worked, workspace types, and proximity of workstation to windows and external walls.

2.2. Sampling scope

Seven Green Mark certified, air-conditioned office buildings in Singapore were surveyed resulting in 666 individual responses. Each participating building had a survey response rate of at least 10 % of the total building occupancy, which is the minimum criteria requested by Green Mark for POE assessment. Our survey scope only included staff who were performing office work and had personal workstations, and excluded any non-office spaces within the same building to maintain consistency. During the survey period, the building facility management team received a survey link from us, and further distributed it to all building occupants (within the office premise under investigate) in the building. The surveyed database is open-sourced and available online [23].

2.3. Statistical analysis

This project utilises an electronic cross sectional survey and is designed to obtain both quantitative and qualitative data. Quantitative data includes all satisfaction responses with the IEQ factors using a 7-point satisfaction scale, while qualitative data includes the reason(s) that caused dissatisfaction in the workspaces. Statistical analyses in this study mainly focused on occupants’ satisfaction responses to address the question: What are the IEQ factors that have highest impact on the overall workspace environment satisfaction?

Applying a mixed effect linear regression model, we identified which of the 17 IEQ parameters (fixed effect) significantly contributed to the overall workspace satisfaction (dependent variable). Equation (3) shows a general format of the linear regression model, where y represents the dependent variable, x_i is the independent variable (i.e., 17 IEQ parameters), α is the y-intercept, and β_i is the slope or trained parameters.

$$y = \alpha + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_i x_i \quad (3)$$

Since multiple occupants were surveyed within the same buildings, the variability in the survey outcome can be influenced either within or between buildings. Occupant’s satisfaction

responses may be biased, as outcomes within the same surveyed building could be inter-related. The advantage in using a mixed effects analysis is that the overall workspace satisfaction within- and between- buildings (random effect) variability could be estimated [24].

Model prediction accuracy was determined by the coefficient of determination R^2 , mean absolute error (MAE), residual standard error (RSE) and model error rate. R^2 shows the proportion of variance explained by prediction. MAE measures the average magnitude between the observed and predicted indices. RSE expresses the variability in the dependent variable unexplained by the model, which means a smaller RSE shows better model fitting. In our context, we assume that an absolute error (difference between observed and predicted value) larger than 0.5 unit can be considered a false prediction (e.g., predicting “satisfied” when in reality the response is “somewhat satisfied”), Equation (4) shows the formula for the model error rate.

$$\text{Model error rate (\%)} = \frac{\text{number of false prediction (error} > 0.5)}{\text{number of total observations, } n} \times 100 \quad (4)$$

Among the 17 IEQ surveyed satisfaction parameters (excluding the overall workspace satisfaction), some could be less significant contributors to the overall workspace satisfaction. Meanwhile, some of these IEQ parameters may be correlated in nature and thus can be combined and represented by a new factor. For instance, two techniques were used to reduce variables for overall workspace environmental satisfaction prediction. The first technique, Akaike information criterion (AIC), is a search method for feature selection. The AIC score penalizes the model if it is over complex to ensure the predictors are optimized (i.e. dropping insignificant variable) with higher goodness-of-fit. A model with a lower AIC score means it is the best to fit the data set, but does not over-fit it [25]. The second technique is Principle Component Analysis (PCA). PCA is an unsupervised machine learning method to reduce dimension of the observations in components that can explain the largest portion of variance [26]. The reduced components were used as new predictors in the mixed effect model to estimate occupant satisfaction with overall environment.

All statistical analyses were performed in R [27]. We use the “lme4” package [28] for the mixed effect model, the R based “stepAIC” function for AIC analysis, and the “psych” package [29] for PCA.

3. Results and Discussion

3.1. Description of the dataset

Table 1 summarizes respondent and workspaces characteristics. A total of 53 % of respondents were male, mainly between 21 and 50 years old, and occupants reported spending more than 30 hours per week in their workspace. Most of the occupants were located in open plan offices with low (< 1.5 m height) or no partitions. 59% of respondents were located near (within 3 m) an external wall and window.

Table 1 Respondents and workspaces characteristics

Parameters and descriptions		Responses rate	
Sex	Female	273	(41 %)
	Male	354	(53 %)
	n.a.	39	(6 %)
Age group	21 – 30	176	(26 %)
	31 – 40	220	(33 %)
	41 – 50	140	(21 %)

	51 – 60	73	(11 %)
	61 above	17	(3 %)
	unknown	40	(6 %)
	Less than 10	74	(11 %)
Working hour (hour)	10 – 30	73	(11 %)
	More than 30	481	(72 %)
	unknown	38	(6 %)
Workspace type	Cubicle with low or no partitions (<1.5 m)	375	(56 %)
	Cubicle with high partitions (>1.5 m)	84	(13 %)
	Enclosed / private office	79	(12 %)
	Others	63	(9 %)
	unknown	65	(10 %)
Distance from external wall	Within 3 m	317	(48 %)
	Further than 3 m	252	(38 %)
	unknown	97	(14 %)
Distance from external window	Within 3 m	390	(59 %)
	Further than 3 m	185	(28 %)
	unknown	91	(14 %)

3.2. Occupants' IEQ satisfaction distribution

Figure 1 shows the distribution of satisfaction responses for each IEQ factor. Overall, respondents were more satisfied with the flexibility of dress code (S = 86 %), artificial light (S = 84 %) and cleanliness (S = 82 %) of their workspace. Factors where dissatisfaction rates were higher than 20 % were sound privacy (D = 42 %), personal control (D = 32 %), air temperature (D = 30 %), level of air movement (D = 27 %), overall privacy (D = 26 %) and noise level (D = 21 %). These results raise an important question: Are these surveyed environments performing poorly in commercial spaces, or is it common to have large variation on satisfaction responses in these IEQ factors within buildings in Singapore?

To answer this question, we compared the satisfaction distribution patterns in Figure 1 to another study conducted by Karmann et al. (2017) which examines 60 commercial buildings in the US using the original CBE survey tool. Despite some variations on the selected IEQ parameters, the satisfaction distribution trend is comparable between the two studies. For instance, dissatisfaction rates for sound privacy (D = 59 %), temperature (D = 32 %) and noise level (D = 42 %) were also found to exceed 20 % in the Karmann et al. study. In addition, sound privacy was the category with the highest dissatisfaction in both studies. This brief comparison shows that the IEQ satisfaction survey results of commercial buildings in Singapore are not worse when compared with US counterparts using the same survey tool. A more important and notable outcome in the present results suggests that achieving a high occupant satisfaction rate is much harder for some IEQ factors compared to others. For example, it is harder to achieve 80 % satisfaction with sound privacy than for electric light. This suggests that a strategy of applying a singular satisfaction rating (i.e. 80% satisfaction target) to all IEQ satisfaction parameters is ineffective. We recommend that target rates of satisfaction should differ for each IEQ factor. Target rates should be based on occupant

satisfaction responses from a large database to achieve reliability and representativeness. For example, the target rates could be based on the average satisfaction score or some other effective rating systems based on the distribution of satisfaction responses. The values presented in the current study may not be fully representative of office buildings in Singapore due to the building selection process and small database. Nevertheless, our results suggest that a more well-rounded definition of satisfaction target rates is needed. A more balanced satisfaction target rate that takes into account the typical ways in which these scores are distributed, could lead to better guidelines for building practitioners prioritizing resources to improve indoor environmental satisfaction in commercial buildings in Singapore.

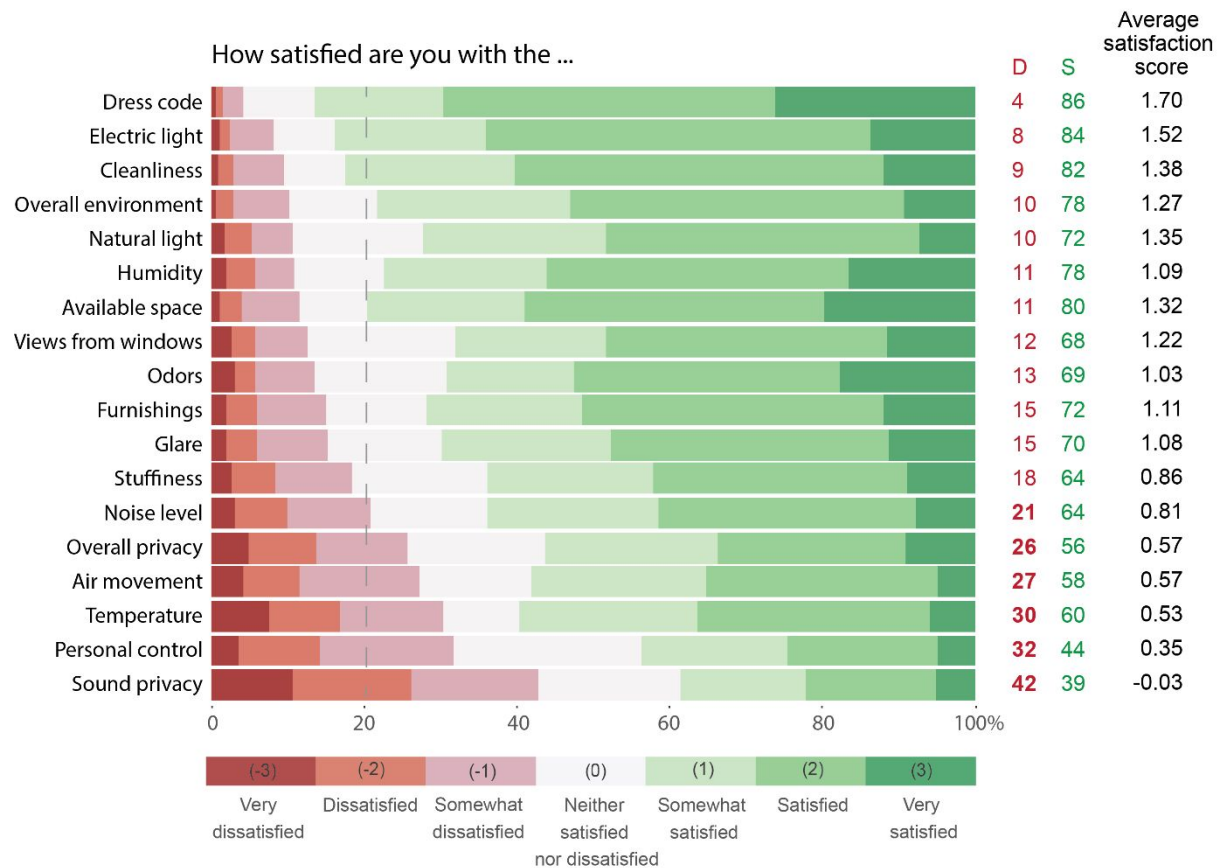


Figure 1. Distribution of occupant satisfaction responses for all IEQ categories. Calculation of dissatisfaction rate (D), satisfaction rate (S) and the average satisfaction score is presented in Equation (1) & (2). The average satisfaction score is calculated as the arithmetic mean of the responses. The grey dotted line indicates the 80 % satisfaction target.

Despite lower satisfaction rates found in some IEQ parameters (i.e. sound privacy, personal control, temperature, air movement, overall privacy or noise level), building occupants were generally satisfied with the overall workspace environment (S = 78 % and D = 10%). This suggests that some IEQ parameters with higher dissatisfaction responses may have a smaller influence on the subject’s overall environmental satisfaction. Detailed analyses and discussions are presented in Section 4.

3.3. Sources of dissatisfaction

Figure 2 summarizes the sources of occupants’ IEQ dissatisfaction in the workspace. Since follow-up questions only pop-up when a dissatisfied response is recorded, and individual participants can select multiple reasons for dissatisfaction in each of the four IEQ category, the aggregate number of dissatisfaction votes, by category, are different and counted separately. In addition, we excluded the “other(s)” responses in our calculation, resulting in a

loss of 2 % to 10 % of dissatisfied responses, depending on category. The reasons for excluding the “other(s)” option is that these dissatisfaction responses are (i) too diversely dispersed (i.e. cannot be grouped into representable categories), or (ii) associated with only one particular building (e.g. there is no greenery near building X), which adds little value to our analysis. Among the four major IEQ categories, we found highest dissatisfaction with the thermal environment (410 votes), followed by sound (316 votes), lighting (250 votes) and air quality (188 votes). The surveyed number of reasons for dissatisfaction is presented in percentages (%) with respect to the total number of votes (excluding “other(s)” option) in each category. Specific dissatisfaction reasons with a percentage > 20 % (i.e. contributing more than one-fifth of the dissatisfaction sample) will be highlighted in our discussion and recommendation of improvements.

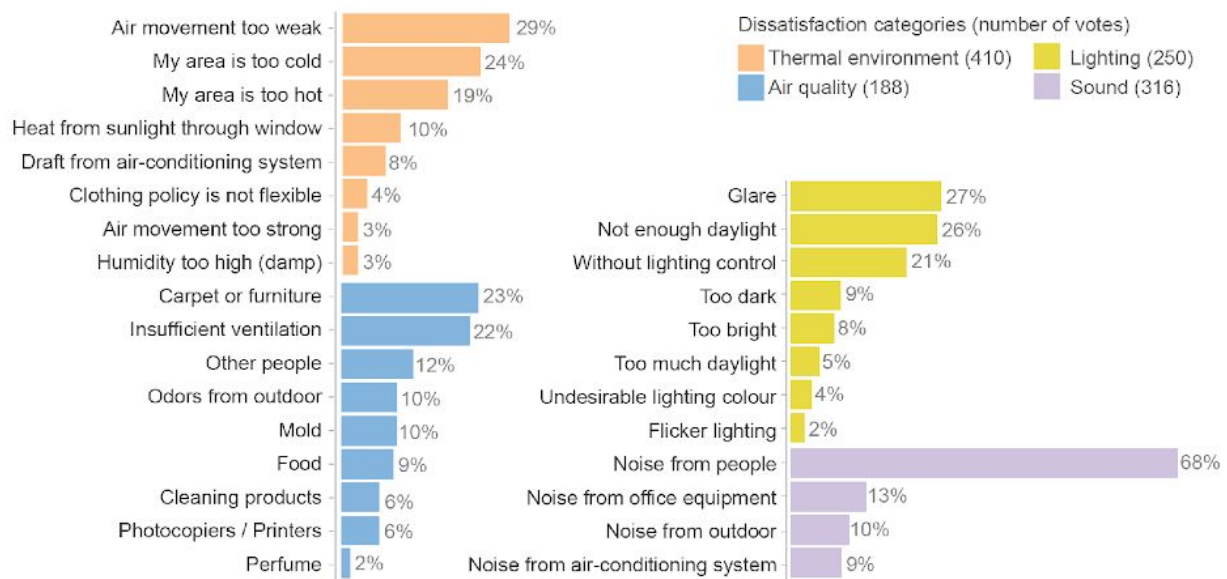


Figure 2 Source of dissatisfaction of different indoor environmental quality (IEQ) categories (the percentage is calculated within the same IEQ category)

We found that occupants were dissatisfied with the workplace thermal environment mainly because of weak air movement (29 %), or that their workstation is too cold (24 %) or too hot (19 %), while the rest of other reasons for dissatisfaction accounted for ≤ 10 % of the total sample. Some results appear contradictory. For example, participants indicated a desire for more air movement, while also reporting that a space was too cold. However, further analysis (see Figure 3) suggests that only 10 % of the respondents reported dissatisfaction with weak air movement while also reporting that they felt cold in their workspace. More occupants expressed a desire for higher air speed because they were too hot (37 %), or simply desired some amount of air movement despite satisfaction with temperature (46 %). This is not contradictory because it is possible occupants prefer more air movement in workspace, not only due to thermal dissatisfaction, but possibly because of air quality perceptions. Elevated air movement improves perceived air quality [30,31] and can effectively disperse the personal CO₂ cloud, thus improving perceived air quality by reducing inhalation of CO₂ [32]. 5 % of the occupants who expressed dissatisfaction with too little air movement, also reported being both too cold and too hot in their workspace. In cases where this occurred, occupants summarized specific past experiences in their responses.

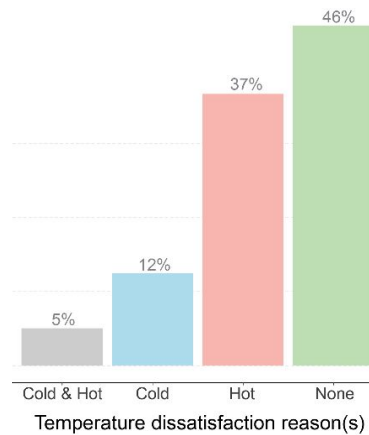


Figure 3 Percentage of dissatisfied reason(s) with temperature for the occupants who were dissatisfied with too weak air movement in workspace

Existing building design criteria of air velocity in air-conditioned occupied space required in Singapore Standard-553 [33] is not to exceed 0.3 m/s. Perhaps providing flexibility on air velocity in the Standard could reduce dissatisfaction with insufficient air movement in the workspace. Increasing indoor air speed by using either ceiling or desk fans enhances the cooling effect perceived by occupants, thus restoring thermal comfort in a warm environment [34]. The effectiveness of this elevated air speed cooling strategy has been confirmed in both chamber experiments [35,36] as well as real office [37] spaces in Singapore. This strategy does not only reduce cooling energy demand, but it simultaneously enhances occupants' thermal satisfaction.

We found overcooling in some of the air-conditioned workspaces. As shown in Figure 2, despite 19 % of the respondents indicating that they were too hot, a quarter of the total dissatisfied count is reflective of occupants being too cold. This finding aligns with a former study of over cooling in other air-conditioned commercial buildings in Singapore [38].

Among the four IEQ categories, air quality received the least dissatisfied responses from occupants (188 votes). Occupants' main sources of dissatisfaction was due to smells from "carpet or furniture" (23 %), "insufficient ventilation" (22 %) and "other people" (12 %). Carpet is known to be one of the major VOC sources in workspaces due to emission from chemicals and supported chemical transformations. Sustainability concerns on proper carpet maintenance is encouraged [39]. Meanwhile, increasing ventilation rates in workspaces could reduce the intensity of odors, and enhance occupants' perceived air quality [40].

In terms of lighting dissatisfaction, the main source of dissatisfaction comes from "glare" (27 %) and "not enough daylight" (26 %), followed by lack of lighting control (21 %). We found that up to 76 % of the occupants who reported glare in the workspace were seated near (<3 m) a window. Surprisingly, among the "not enough daylight" dissatisfaction responses, 43 % of the occupants were also located near a window. We suspected that occupants are closing blinds to protect themselves from glare. Manual blinds enable users to block out unwanted daylight and glare, however, these blinds often remain drawn, even during cloudy or overcast days [41]. Such practice limits the daylighting potential, thus increasing the reliance of indoor lighting for indoor illumination [41,42]. Incorporation of effective design that includes light shelves and shading devices to maximize daylight, while reducing glare, could be a solution to minimize lighting dissatisfaction [43]. In addition, providing simple manual control of lighting (e.g., a desk lamp) can enhance occupant acceptability of lighting in office space [44].

The most reported source of dissatisfaction came from “noise from people” (68 %). This was also a major contributor to the of dissatisfaction with sound privacy (D = 42 %) and noise level (D = 21 %) (Figure 1). Expectedly, 90 % of dissatisfaction with “noise from people” was reported in open plan offices, and 75 % of these respondents were those housed in cubicles with low (<1.5 m) or no partitions. Providing private office to everyone may not be possible, however, having high partitions (>1.5 m) could partially reduce noise from people and improve sound privacy, but its effectiveness has been challenged as this design may also reduce the ease of communication between colleagues [45]. In fact, the dissatisfaction rate of “sound privacy” from occupants working in spaces with high partitions (>1.5 m) was still high (D = 28 %) in this study. Alternatively, having several easily-available, temporary, quiet offices could provide employees with a quiet place for times when deep focus is needed, while still affording space for collaborative environments within the whole workspace [46]. In addition, establishing behaviour protocol for sound privacy in the office, paired with acoustical treatment on sound absorbing ceilings and walls (or even sound masking systems), could also significantly enhance acoustic comfort in workspace [47].

4. Overall environment satisfaction contributors

In this section we analyse which variables contribute the most to overall environmental satisfaction. We applied correlation analysis on the 18 IEQ satisfaction responses to elicit the relationship between parameters. Next, we conducted principle component analysis (PCA) to identify the possible new factors (or components) that emerge between the multiple IEQ parameters. Lastly, we analysed the significance of the factors in predicting overall environment satisfaction by using multiple linear regression and mixed effect model.

4.1. Correlation analysis

Figure 4 presents the correlation analysis of the 18 IEQ satisfaction responses. It visualizes only the moderate (0.5-0.8) and strong (>0.8) correlations. Satisfaction with the overall environment moderately correlated with 10 of the other parameters including cleanliness, stuffiness, furnishings, personal control, odors, noise level, humidity, air movement, electrical and natural light. This suggests that multiple factors may influence people’s satisfaction with their overall workspace environments. Additionally, we observed that some parameters were inter-correlated within a particular cluster. For example, satisfaction with stuffiness, odors, air movement, humidity and temperature -- parameters that all contribute to perceptions of a space’s air -- were moderately correlated. Similarly, we found moderate relationships between satisfaction with natural light, electric light and view from one’s window (i.e., parameters of visual perceptions), noise level and sound privacy (which influence acoustical perceptions), and furnishings, available space and overall privacy (which contribute to workspace layout). In addition, the results showed satisfaction with personal control was correlated with air movement, temperature, natural light and sound privacy; which suggests that higher levels of control within personal workspace (i.e. operation of fans, temperature sensors, window blinds or working in an enclosed private room) could enhance satisfaction with other IEQ parameters. The correlation analysis suggests covariates exist among the 18 IEQ parameters. Therefore, we conducted a PCA to explore the clustering of satisfaction parameters to identify similar underlying measurements before evaluating the contributors of overall environmental satisfaction.

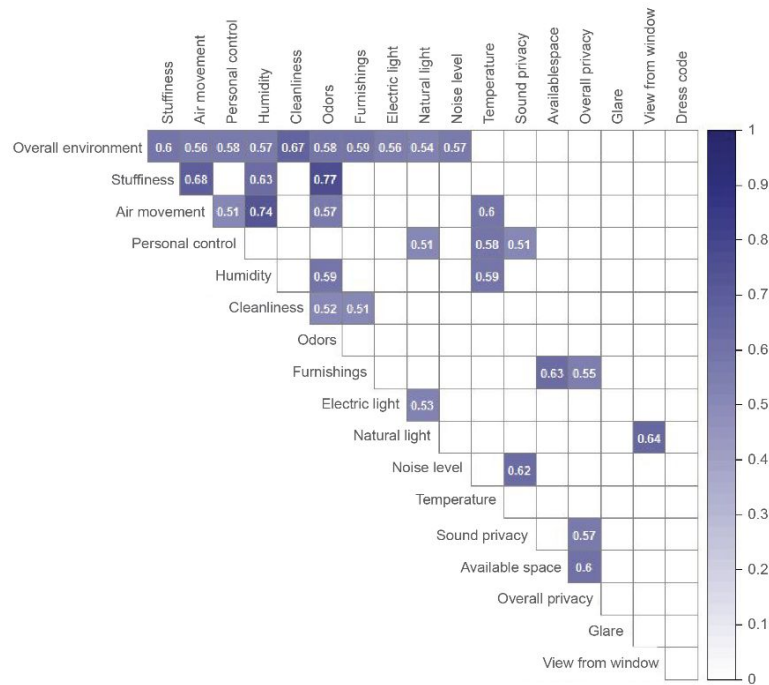


Figure 4 Correlation matrix of the 18 satisfaction parameters. Only moderate (0.5-0.8) and strong (>0.8) correlations are presented.

4.2. Principle component analysis (PCA)

We removed 84 incomplete satisfaction responses in the database before conducting the PCA. We performed six PCAs ranging from 7 to 12 factors from 17 IEQ satisfaction responses (exclude satisfaction with overall environment). These PCAs respectively accounted for 78 %, 82 %, 85 %, 87 %, 89 % and 91 % of the total variance. All six cases (from 7 to 12 principle components) are included for further analysis in the next section. Among the six PCA structures, the solution with 9 components reveals a higher interpretability compared with the other solutions[48]. We breakdown inter-related factors when more components are introduced (i.e. 10, 11, or 12), while less interpretable components combined with non-related IEQ parameters could be observed when the approaches with fewer components are selected (i.e. 7 or 8). For example, in the 8 factor solution, there is one component comprised of satisfaction with electric light and cleanliness, making this factor uninterpretable. Table 2 demonstrates the PCA structured with 9 factors as an example among the six PCA solutions. It shows the factor loadings for the nine components (header) with respect to 17 satisfaction responses, and those with loadings greater than 0.5 are highlighted. Under the same solution, IEQ satisfaction parameters with higher loadings were grouped. The naming of each factor is dependent upon the nature and characteristics of the grouped IEQ parameters. For example, we named the first factor Perceived Air Quality (PAQ) because the four IEQ parameters with highest loadings (stuffiness, odors, air movement and humidity) under this factor are all related to occupant perceptions of the air. The same logic is applied for naming the other factors in Table 2. The factors are arranged, from left to right, in decreasing order of proportional variance within the PCA.

The dominating components in Table 2 were “PAQ”, “Layout”, “Acoustics”, “Thermal” and “Window”. Each of these factors is comprised of more than one IEQ satisfaction parameter and explained >10 % of the variance within the dataset. The remaining components, “Lighting”, “Glare”, “Clothing” and “Cleanliness”, were mainly comprised of single IEQ parameters and explained less variance in our surveyed dataset. One possible reason for lower

variance observed among these factors could be due to the static nature of these parameters as they may not change vastly in the building environment. For example, within working hours, the schedule for electric lighting in a space is typically fixed and does not change much; however, the views from a window, and exposure to natural light, may change depending on where you are located in the workspace. Although the assessment of personal control loads heavily on the “Thermal” factor, it loads moderately (0.3 – 0.4) on the “Acoustic”, “Window” and “Lighting” factors as well. These findings are consistent with the correlation analysis reported above. In addition, we found that satisfaction with overall privacy has high loadings on both the “Layout” and “Acoustic” components. Similarly, satisfaction with air movement has strong loadings on the “PAQ” and “Thermal” environment components. These results suggests that it may be logical to presume that satisfaction with certain IEQ aspects (e.g. overall privacy and air movement) may contribute to occupants’ perceptions with more than one environmental factor. In other words, occupants’ satisfaction with overall privacy, may influence the way they perceive the layout and acoustics within space.

Table 2 Factor loading for 17 IEQ satisfaction parameters from PCA. Parameters are grouped (loadings > 0.5) by their contribution to each explainable component. *PAQ stands for perceived air quality.

	PAQ*	Layout	Acoustics	Thermal	Window	Lighting	Glare	Clothing	Cleanlines
Stiffness	0.84	0.11	0.19	0.13	0.15	0.15	0.09	0.1	0.08
Odors	0.82	0.05	0.14	0.04	0.13	0.23	0.05	0.1	0.26
Air movement	0.67	0.16	0.14	0.51	0.12	0.05	0.18	0.04	-0.02
Humidity	0.66	0.22	0.04	0.48	0.16	-0.08	0.14	0.15	0.09
Available space	0.12	0.85	0.11	0.09	0.13	0.05	0.16	0.12	0.12
Furnishings	0.21	0.71	0.14	0.16	0.16	0.25	-0.02	0.1	0.29
Overall privacy	0.05	0.7	0.51	0.13	0.16	0.06	0.03	0	-0.1
Sound privacy	0.19	0.21	0.85	0.14	0.11	0.09	0.01	0.04	0.01
Noise level	0.15	0.17	0.76	0.16	0.1	0	0.15	0.11	0.28
Temperature	0.26	0.16	0.16	0.85	0.03	0.04	0.07	0.06	0.09
Personal control	0.13	0.07	0.4	0.61	0.32	0.36	0.07	0.07	0.18
Views from window	0.21	0.13	0.11	0.07	0.9	-0.02	0.08	0.07	0.08
Natural light	0.14	0.23	0.15	0.13	0.75	0.34	0.15	0.05	0.08
Electric light	0.3	0.25	0.07	0.11	0.19	0.77	0.26	0.07	0.13
Glare	0.21	0.12	0.12	0.13	0.17	0.19	0.89	0.03	0.1
Dress code	0.19	0.14	0.1	0.09	0.08	0.06	0.03	0.95	0.07
Cleanliness	0.29	0.25	0.23	0.16	0.16	0.14	0.13	0.09	0.78

4.3. Model prediction

We established models with different predictor variables to estimate occupant’s satisfaction with the overall workspace environment. The intention of the model prediction is to rank the input parameters (predictors) as a function on their impacts to the overall workspace environment satisfaction (dependent variable). The results could inform building practitioners on how to improve the overall workspace environment satisfaction by giving priority to the parameters that have the highest influence.

We used three methods to select the model parameter inputs, aiming to compare the model prediction performance with different input parameters. The first method is a multiple linear regression with all 17 IEQ parameters and another regression with only the significant IEQ parameters as inputs using the Akaike information criterion (AIC) technique. The second method is a linear mixed effect model using the IEQ parameters as the fixed effects and “Building ID” as the random effect inputs. The third method uses the components (7 to 12 factors) in the computed PCA as predictors in a linear mixed effect model. We applied a 5-fold cross validation technique in the analysis and partitioned 80 % and 20 % of the data, respectively, for model training and validation. Table 3 summarizes the statistical performance for all models. All metrics in each model are presented as a mean value from the 5-fold cross validation. The trained parameters (i.e., the beta estimate, β_e) for each predictor

in the Linear full, Linear AIC, Mixed full, Mixed AIC and PCA 9 models are summarized in the Appendix Table A.1. Since the PCA components are data driven predictors from our database, some of the components may not even have proper physical meaning. Limited contribution is expected by showing the trained parameters on those non-interpretable components; thus we choose only the PCA 9 model as an example in Table A.1 while dropping the others.

Table 3 Statistical performance of different models for overall environment satisfaction. Each metric is calculated as a mean value from the 5-fold cross validation.

Model	No. of variables	Random effect (Building ID)	R ²	MAE	RSE	Model error rate (%)
Linear full	17	-	0.69	0.48	0.66	37.5
Linear AIC	9	-	0.69	0.48	0.67	39.1
Mixed full	18	Y	0.70	0.47	0.65	35.3
Mixed AIC	10	Y	0.69	0.47	0.66	36.3
PCA 7	8	Y	0.67	0.50	0.67	36.5
PCA 8	9	Y	0.70	0.48	0.66	35.8
PCA 9	10	Y	0.70	0.47	0.65	33.9
PCA 10	11	Y	0.70	0.47	0.65	33.5
PCA 11	12	Y	0.70	0.47	0.65	33.5
PCA 12	13	Y	0.70	0.47	0.65	33.5

Initial observation suggested that the prediction performance did not vary much across models. A mean R² value of 0.7 suggests that 70 % of the variance in the satisfaction with overall environment can be predicted by corresponding variables in each model. An average magnitude of the errors is approximately 0.5 units for each model (MAE ~ 0.5). The average standard error of model prediction based on residuals is between 0.65 – 0.67 corresponding to 33 % ~ 39 % of the error rate. This suggests that for about two-thirds of the time, we have a correct prediction using these models. The AIC technique dropped 8 variables when compared with a full model, while it did not impede prediction performance. In the AIC modified linear model, the remaining 9 variables were cleanliness ($\beta_e = 0.24$), noise level (0.14), electric light (0.13), furnishings (0.12), stuffiness (0.11), humidity (0.09), dress code (0.09), views from window (0.08) and personal control (0.05). Meanwhile, the “Building ID” as a random effect explained ~1.5 % of the variance in our surveyed database, which slightly improved the model error rate by 2.2 – 2.8 % when compared with the linear regression model. The magnitude and sequence of the beta estimate (β_e) for each variable in the mixed AIC model was found very similar to that which was reported in the linear AIC model. Increasing the number of principle components from 7 to 12 in the PCA improved the model error rate by 3 %, but the improvement rate flattened when 9 components were introduced in the model. This indicated that an adequate number of components, not too much or too little, is essential to interpret occupants’ satisfaction with overall workspace environment. In other words, the data may vary, but further increasing of the number of factors as predictor variables will not bring additional improvement to the model.

Table 3 shows that the prediction performance for all presented models are not vastly different from each other. The difference is therefore contributed by input parameters. Among all the models, the two most comparable models are the “Mixed AIC” and “PCA 9”, in terms of the number of variables (9 fixed effects + 1 random effect) and the model performance. However, the significance of contributing variables is slightly different across the methods. Analyses on the model inputs are presented as follows.

4.3.1. Surveyed parameters as input (Mixed AIC)

In the mixed AIC model, the contributors in predicting overall environment satisfaction were satisfaction with cleanliness ($\beta_e = 0.24$), noise level (0.15), furnishings (0.13), electric light (0.11), stuffiness (0.10), humidity (0.10), personal control (0.09), views from window (0.08)

and dress code (0.07). This method shows satisfaction with cleanliness has double the impact on overall environment satisfaction compared to most of the other variables. These findings may differ greatly between offices in Singapore and the majority of the other buildings within the CBE dataset (data mainly obtained in the US). Within the CBE dataset, the most important parameter for overall workspace satisfaction is satisfaction with the amount of space, while the least important parameter is satisfaction with workspace cleanliness [8].

These stark differences across building databases suggest that perhaps other factors (such as culture or occupant expectations) may be driving these perceptions. For example, available office space per occupants has declined over the years in Singapore due to high population density and high rental cost [49], while the designated amount of workspace area per person in the US is almost double that in Singapore [50]. We propose that Singaporeans may have adapted to a smaller workspace environment, resulting in more flexible expectations on how much workspace they are given—therefore resulting in the “amount of space” having little impact on overall environmental satisfaction. Future work should explore how cultural differences may influence occupant perceptions like these.

We also found satisfaction with cleanliness to be the most important parameter for overall workspace satisfaction in Singaporean spaces. Previous work has shown workspace cleanliness to have a positive impact on occupant satisfaction with one’s office environment and productivity [51]. Psychological research examining the overall concept of “cleanliness” suggests that cleaning behaviours work to eliminate feelings of disgust. Further, when people feel something is clean, this evokes a sense of purity which has been shown to lead people in general to make less harsh moral judgements of others around them [52]. Perhaps a cleaner workspace environment could, to some degree, reduce the effect of dissatisfaction caused by other environmental factors, leading to higher overall satisfaction with the environment. Perceived cleanliness of a space may mask perceptions of other environmental factors, allowing occupants to overlook some shortcomings of a space (just as perceptions of cleanliness allows for the overlooking of shortcomings of other people). To shed further light on this possibility, we split the satisfaction responses of those satisfied and dissatisfied with cleanliness as shown in Figure 5. Despite a smaller sample size (10% of the total database), data from the dissatisfied workspace cleanliness dataset is evenly represented by the sampled buildings (indicating responses are not dominated by a single unclean building). What these findings reflect are that if the occupants who are dissatisfied with cleanliness in their workspace, are also likely dissatisfied with other IEQ parameters (including the overall environment) compared to those who were satisfied with cleanliness. This suggests that by maintaining a clean environment, an organization could improve satisfaction with their workspace in general in Singapore. We do not have clear evidence as to why Singaporean workers may put a higher emphasis on cleanliness compared to those in the US. This difference could be the result of the “Keep Singapore Clean” campaigns. This has been a series of campaigns put forth to the public over the past 50 years in an effort to make and keep Singapore clean [53]. A public cleanliness satisfaction survey resulting in over 2000 Singaporean respondents, showed that 94% of the respondents agree Singapore is a clean city and 98% of them take pride in keeping Singapore clean [54]. This sense of pride and these cultural expectations may be a large contributor in how Singaporeans conceive of and define “cleanliness”. Future work should continue to explore to see whether or not cultural differences like this persist across buildings and occupant perceptions worldwide.

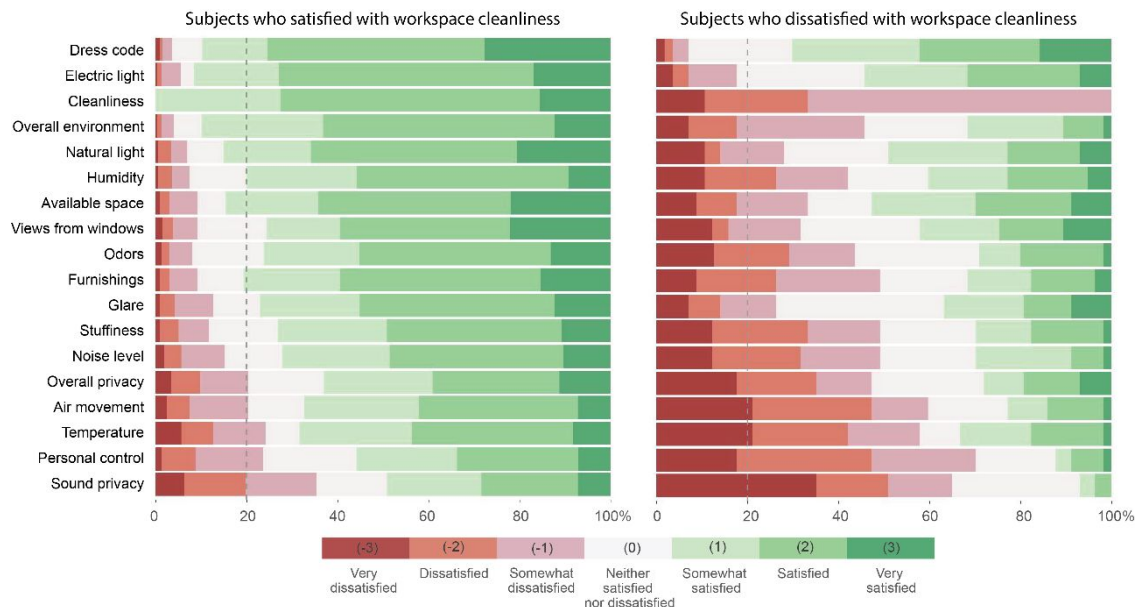


Figure 5 Distribution of occupant satisfaction responses for subjects who are satisfied (left) and dissatisfied (right) with cleanliness in their workspace

4.3.2. Integrated components as input (PCA 9)

Compared to analysing the raw survey data, the PCA approach based on dimension reduction and data variance allows us to cluster multiple related variables into more representative components. Using the regenerated vectors from the “PCA 9” solution, we evaluated the impact of each component to the overall environmental satisfaction, and the resulting factors were “PAQ” ($\beta_e = 0.45$), “Cleanliness” (0.39), “Acoustics” (0.39), “Layout” (0.35), “Window” (0.33), “Thermal” (0.33), “Lighting” (0.24), “Clothing” (0.19) and “Glare” (0.15). All nine components were significant ($p \leq 0.05$) in this model. Comprised of four related variables, including air movement, humidity, odors and stuffiness (see Figure 4 and Table 2), the “PAQ” factor has the highest impact on overall environmental satisfaction. In another study, an environmental workspace survey found that only 1 out of 4 employees reported the air quality as optimal to them, additionally, half of respondents claimed that poor air quality in workspace affected their productivity [22]. Meanwhile, participants’ responses to perceived air quality could be influenced by multiple factors, including air movement, temperature, humidity and indoor pollutants [31,55]. This finding suggests that some IEQ parameters alone may have less impact on overall environmental satisfaction, but the impact can be significant if several related factors are combined together.

Comprised of only one variable, “Cleanliness” still proved to be the second most important component in the “PCA 9” solution. This further highlights the ways in which the expectation of a clean environment may influence occupants as they consider overall workspace satisfaction. Equally as important as cleanliness, the “Acoustics” factor, comprised of noise level, sound privacy and overall privacy, also has a significant impact on overall environmental satisfaction. It should be noted that the “Acoustics” factor is not only weighted by noise level, but also privacy. A similar component was also identified by Veitch et al., (labelled the “privacy/acoustics” factor), and was shown to be one of three major features in determining overall workspace satisfaction in the COPE study [21]. Similar to previous findings, the “Lighting”, “Clothing” and “Glare” factors were relatively less important in

predicting overall environmental satisfaction due to little variation of these parameters in workspace.

Although our analyses show cleanliness in workspace is the most important single parameter that affect occupants' satisfaction with the overall workspace environment in Singapore, we should not overlook other parameters which have smaller impacts. The results show that the overall indoor environment quality is not contributed by just one parameter. The PCA approach suggests that even though significance for an individual variable is small, the integration of multiple related IEQ variables could also substantially impact overall environmental satisfaction. The results presented in this study could inform building practitioners when prioritizing allocation of resources to improve tenant satisfaction with the overall workspace environment. In addition, the findings can help to create meaningful IEQ benchmarks based on occupant satisfaction. These IEQ benchmarks allow building owners and facility manager to compare building performance between their buildings, and other similar commercial buildings in Singapore.

5. Limitations

A major limitation of this pilot study is the small building and individual sample size (7 buildings and 666 respondents). This may influence the accuracy of the analysis, especially for instances in which there is limited variance available in the PCA. The existing database is part of larger longitudinal project. We are continuously surveying buildings with the intention of developing an IEQ benchmarking system for commercial buildings in Singapore. Additionally, our survey tool has been adopted by the Green Mark scheme for post-occupancy evaluation assessment in Singapore [17]. The analysis methods presented in this study can be a reference for government agencies to reproduce the findings with more surveyed buildings and a representable database across Singapore.

The analyses of ordinal data (satisfaction vote) using linear regression model may be of concern. Therefore, we summarize the analysis using a proportional odds ordinal logistic regression to evaluate the significant parameters for overall workspace satisfaction in the Appendix Figure A.1. We showed that the order of importance of each parameter was very similar (or identical to the PCA components input) between the linear regression and the proportional odds ordinal logistic regression approach. The reason that we have chosen to adopt a linear regression in our analysis, instead of proportional odds ordinal logistic regression approach, is because the beta estimate value (β_e) in a linear regression is generally easier to understand and interpret. In addition, the mixed effect linear model allows us to verify the variance of different surveyed buildings by introducing "Building ID" as a random effect in the model, which it is not available in the proportional odds ordinal logistic regression approach.

6. Conclusions

We modified the CBE Indoor Environmental Quality (IEQ) Occupant Survey to conduct IEQ satisfaction assessments in 7 commercial buildings in Singapore (666 respondents). Overall satisfaction with the environment was 78 %. People were most satisfied with flexibility in dress code (S = 86 %), electric light (84 %) and cleanliness (82 %). We found dissatisfaction rates higher than 20 %, for sound privacy (D = 42 %), personal control (32 %), temperature (30 %), air movement (27 %), overall privacy (26 %), and noise level (21 %). These results suggest that achieving a high occupant satisfaction rate for some IEQ factors is harder than others. This work suggests that applying singular satisfaction ratings (i.e. 80% satisfaction criteria) for all IEQ parameters is inappropriate; and instead, developing satisfaction target rates for each IEQ factor could provide a more effective measure of occupant satisfaction

with indoor environment parameters. We also found that occupants are dissatisfied with the thermal environment in workspaces in Singapore mainly because of weak air movement and the space being too cold. In addition, the most prominent source of dissatisfaction in a Singaporean workspace comes from noise generated from other people. Correlation analysis suggested satisfaction with the overall environment was associated with different IEQ variables. We found that cleanliness was the most important individual variable affecting an occupant's satisfaction with his or her overall workspace environment. We also found components such as Perceived Air Quality, Acoustics, Layout and Thermal - were comprised of multiple less significant, but inter-related IEQ variables - and also provide substantial influence over perceptions of overall workspace environmental satisfaction. In the future, this study will continue to survey more buildings, in an effort to build a substantial database that may be useful in developing an IEQ benchmark for commercial building in Singapore.

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Appendix

Table A.1 Trained parameters (beta estimate value, β_e) for the models presented in Table 3

Parameters	Models using surveyed data as input (beta estimate value, β_e)				PCA 9 model	
	Linear full	Linear AIC	Mixed full	Mixed AIC	Components	Beta estimate, β_e
Intercept	0.02	0.02	0.06	0.06	Intercept	1.24***
Temperature	0.02		0.04		PAQ	0.45***
Humidity	0.06	0.09**	0.05	0.10**	Cleanliness	0.39***
Air movement	0.03		0.03		Acoustics	0.39***
Dress code	0.09**	0.09**	0.07**	0.07**	Layout	0.35***
Available space	0.03		0.02		Window	0.33***
Overall privacy	0.00		0.00		Thermal	0.33***
Furnishings	0.10***	0.12***	0.09***	0.13***	Lighting	0.24***
Stiffness	0.07*	0.11***	0.06	0.10***	Clothing	0.19***
Odors	0.05		0.05		Glare	0.15***
Electric light	0.10**	0.13***	0.08*	0.11***		
Natural light	0.06		0.07*			
Glare	0.01		0.01			
Window view	0.06*	0.08***	0.06*	0.08***		
Noise level	0.14***	0.14***	0.14***	0.15***		
Sound privacy	0.01		0.01			
Personal control	0.04	0.05*	0.06*	0.09***		
Cleanliness	0.23***	0.24***	0.22***	0.24***		

p-value: “***” < 0.001; “**” < 0.01; “*” < 0.05

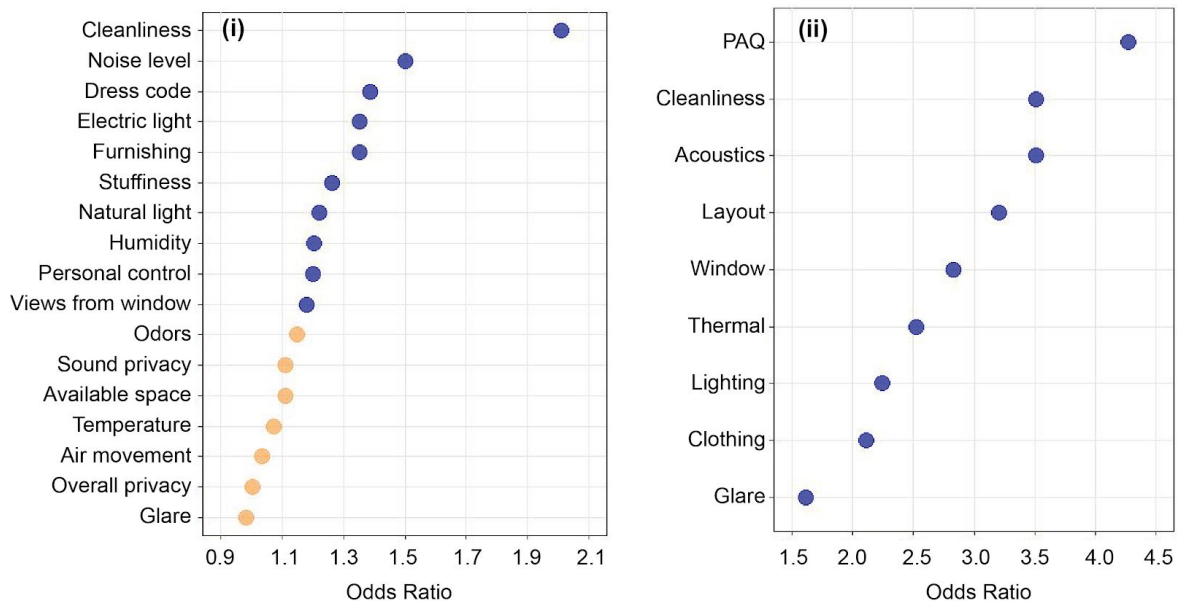


Figure A1 Odds ratio for (i) satisfaction with 17 indoor environmental parameters and (ii) 9 components evaluated from principle component analysis. Odds ratio data points in blue means the corresponding parameter is significantly contributing to overall workspace satisfaction ($p < 0.05$).

Proportional odds ordinal logistic regression was applied to analyse the relationship between different predictor inputs and satisfaction with the overall workspace environment. We use the “polr” function in “MASS” package in R to conduct the analysis. Figure A1(i) shows the odds ratio (OR) for satisfaction with the 17 indoor environmental quality (IEQ) parameters. The parameters are arranged in descending order of OR value. Odds ratio data points in blue means the corresponding parameter is significantly contributed to overall workspace satisfaction. Our analyses suggested that satisfaction with odors, sound privacy, available space, temperature, air movement, overall privacy and glare were insignificant parameters ($p > 0.05$) for overall workspace satisfaction (point in orange colour). The satisfaction with workspace cleanliness (OR = 2.01) was the most important parameter for workspace

satisfaction. This means the overall workspace satisfaction are 2 times more likely to be increased by improving satisfaction with workspace cleanliness than the case when workspace cleanliness is not improved. The next important parameters for overall workspace satisfaction were noise level (OR = 1.50), dress code (1.39), electric light (1.35), furnishing (1.35), stuffiness (1.26), natural light (1.22), humidity (1.20), personal control (1.20) and views from window (1.18). Except the satisfaction with dress code and natural light are highlighted in the proportional odds ordinal logistic regression method, the importance for the rest of other parameters have not much difference from the results that evaluated by the linear regression approach in section 4.3 of the manuscript.

Figure A1(ii) presents the odds ratio for the 9 principle components that evaluated from the surveyed database (Table 2 in the manuscript). All nine components contributed significantly to workspace satisfaction ($p < 0.05$). The significance for each component, represented by odds ratio, was Perceived air quality (PAQ) (OR = 4.27), Cleanliness (3.51), Acoustics (3.51), Layout (3.20), Window (2.83), Thermal (2.52), Lighting (2.25), Clothing (2.11) and Glare (1.61). This order of significance to overall workspace satisfaction by odds ratio is exactly the same when compared with the order of estimate that analysed using linear regression approach in the manuscript.