Evaluation of an indoor environmental quality model for very small residential units

Research Article

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Abstract

This study investigates the indoor environmental quality (IEQ) responses from occupants living in very small residential units that are unique to Hong Kong. Through the changes in environmental parameters, including thermal, indoor air quality, visual and aural, the study demonstrates that the overall IEQ acceptance in these units is different from the one in general residential building environments. Results show that occupants of these units are more sensitive to warmth and operative temperature change as compared to occupants of general residential buildings. A small variation of thermal acceptance suggests that the small unit occupants have already developed certain degree of tolerance to hot conditions. The adaptation to the reality of a hot environment is also reflected in the overall IEQ acceptance. It is believed that very small space residents have developed tolerance and adaptation to an unchangeable reality, changing environmental conditions does not necessarily alter their acceptance of individual IEQ aspects and overall IEQ.

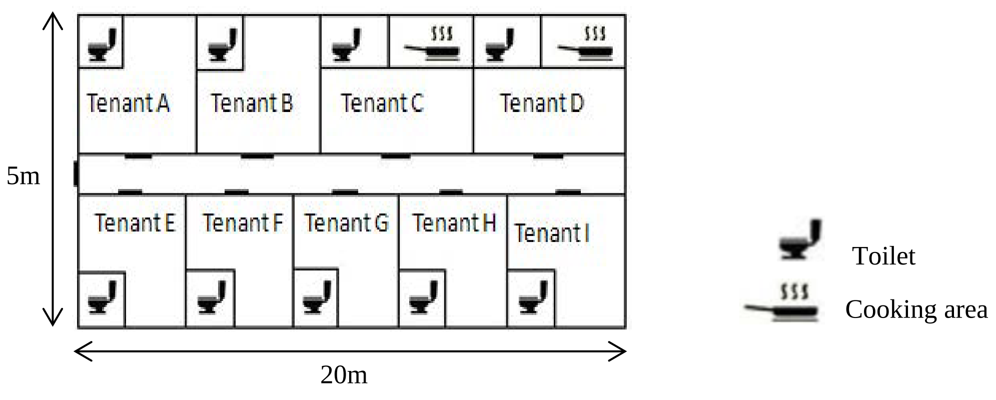
Keywords

Indoor environmental quality (IEQ), Residential buildings, Occupant, Acceptance, Tolerance

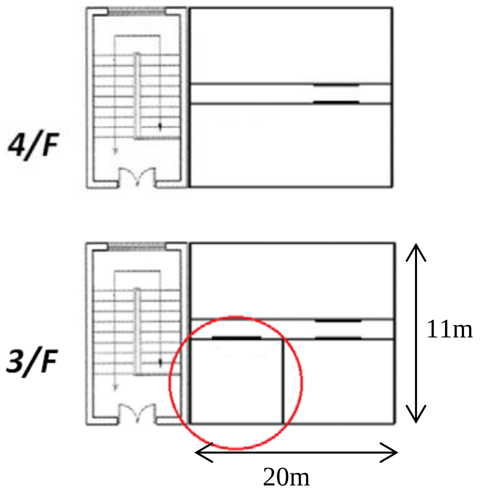
Introduction

Hong Kong, a metropolitan city of over 7 million inhabitants, has been facing a housing shortage for years due to limited land supply. This leads to the emergence of very small living environments including temporary shelters, rooftop structures, bedspaces, cocklofts and subdivided units (SDUs).[1] These environments are usually high in occupancy density and poor in hygiene conditions as compared with general private and public residential units.[2-4] According to CUHK Institute of Future Cities, the average per capita living area for these environments is 4.44 m^2 ca^{-1} [5] and it is smaller than the minimum living standards for USA (14 m^2 ca^{-1}), Japan (19 m^2 ca^{-1}), Taiwan (7 m^2 ca^{-1}), South Korea (12 m^2 ca^{-1}) and Hong Kong (6.5 m^2 ca^{-1}).[6] Reportedly, there were about 66,900 small residential units with 171,300 residents in Hong Kong in 2013.[2] A survey conducted in 2015 estimated that over 199,900 residents were living in approximately 90,000 small residential units in Hong Kong.[7]

Figure 1 show some examples of the floor plans of typical SDUs in a government report.[7] Figure 1(a) shows example SDUs partitioned from an apartment of 5m × 20m; the example units are equipped with private toilets and independent cooking space in an area of about 7–10m^2. The circle in Figure 1(b) illustrates an SDU created in the quarter on 3/F by newly constructed wall and a wall opening added (while 4/F plan shows no alteration for comparison). The unit can be further sub-divided into smaller units by additional walls and openings as shown in Figure 1(c).



(a)



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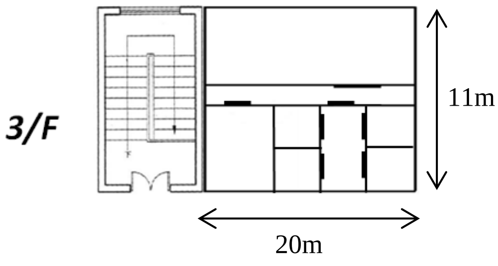

(c)

Figure 1. Example arrangement of subdivided units

Physical environmental parameters of the living environment such as air temperature, relative humidity, acoustics, air quality, lighting, ventilation and air distribution are all interrelated with respect to occupant comfort. An integrated approach is often used to address IEQ by using multivariate-logistic regression model. This model defines IEQ with the four above-mentioned aspects in a 2-fold process, occupant responses towards individual IEQ aspect and to the overall IEQ, i.e. a double layer logistic model. Multivariate-logistic model for IEQ acceptance for offices, classrooms and residential buildings in Hong Kong have been developed with applications demonstrated.[8-10] In a previous study, an overall IEQ logistic regression model for general residential building environments was developed based on occupant acceptance of the four aspects.[8] The model can be used as a quantitative assessment criterion for similar residential environments where various human response factors matter (e.g. occupant comfort, well-being, health and productivity). It is a known fact that high occupancy density has the effect of magnifying the variability of environmental conditions. As the extreme environmental conditions in a very small living environment are unbearable to most people, responses of those living under such conditions to IEQ may not follow the trends described in other studies on IEQ acceptance in residential environments. Nevertheless, a reliable IEQ model with robust predicting ability and small discrepancy between predicted and actual acceptance is crucial to sustainable building development.[11] On top of that, model updating to minimize the difference between additional measured data and prediction is also highly preferred.[12-13]

This study investigates the IEQ responses from occupants living in very small residential units in order that the above-mentioned IEQ logistic regression model can be improved by taking small living spaces into account.

Methodology

Survey data and on-site field measurements were collected through individual interviews conducted in small residential units in Hong Kong from October to December 2016. A total of 52 residents were interviewed: 8 living in single units, 37 in refurnished SDUs (all types included, see Figure 1(a)–(c)), 1 in a bedspace unit and 6 in rooftop houses. All interviewees were asked a set of questions related to perceive IEQ, and their outfits and activities of daily living were recorded to determine the clothing values and metabolic rates using ASHRAE Standard 55.[14] While the single units and rooftop houses were bigger in size with a floor area range of 18.6 to 37.2 m^2, the SDUs and bedspace were smaller with a floor area range of 6.0 to 18.6 m^2.

Based on the previous study, the indoor environmental parameters included in the measurements were indoor air temperature (T_a), radiant temperature (T_r), indoor air velocity (V_a), relative humidity (RH), carbon dioxide (CO_2), horizontal illuminance level and equivalent noise level.[8] While CO_2 acted as a surrogate indicator for IAQ, horizontal illuminance and equivalent noise levels were indicators for the visual and aural environments respectively. The remaining parameters (i.e. T_a, T_r, V_a and RH) were used for the calculation of operative temperature (T_o) and predicted mean vote (PMV) to evaluate the thermal environment. Since most living spaces in this study were extremely small and without partitioning, a 15-min physical measurement was carried out which was considered to be 'steady' for assessing an occupant response to indoor environmental factors. This protocol has been used in a previous IEQ study in average residential buildings in this region[8] and therefore direct comparisons with previous data can be made with the data collected in this study.

The way in which occupants perceive indoor environmental conditions may affect their comfort. The interviewees were invited to rate thermal sensation (ζ_1) via a seven-point semantic differential scale: cold (–3), cool (–2), slightly cool (–1), neutral (0), slightly warm (+1), warm (+2) and hot (+3).[14-15] Besides, they were asked to evaluate IAQ acceptance (ζ_2) via a five-point scale: very good, good, neutral, bad and very bad. With a maximum score of 100, points were also awarded by them to aural comfort (ζ_3) and visual comfort (ζ_4). Eventually, they were required to determine the overall IEQ acceptance.

To validate the responses, a direct polar acceptable/unacceptable question "Is the thermal environment/indoor air quality/aural level/visual level of the indoor living environment perceived by you satisfactory?" was used.[16] Validation was based on the consistency of the answers to the differential and polar questions. For the thermal environment differential scale, ζ_1=–3/–2/+2/+3 are considered as unacceptable thermal vote and ζ_1=–1/0/+1 as acceptable. If the respondent voted unacceptable for the differential question but voted acceptable for the polar question, the contradictory response was considered as invalid. Extreme cases (e.g. an acceptable visual environment with a score of 0) were also considered to be invalid.

Results and discussion

The 52 per capita apartment areas surveyed ranged from 2.3 to 16.3 m^2 ca^{-1} with an average of 5.7 m^2 ca^{-1}. Although this average is comparable to the average value of 5.8 m^2 ca^{-1} found in a former survey by the government on general SDUs [7] (p>0.05, t-test), it is well below the Hong Kong average living space of 13.1 m^2 ca^{-1} (p<0.0001, t-test) provided in another report by Hong Kong Housing Authority.[17] Most of the apartments are equipped with window-type air-conditioner, but 85% of them were not operating during the interview. Atmospheric information was also recorded with average outdoor air temperature of 26.9 °C (2.2) and relative humidity 71.3% (13.5).

Table 1 summarizes the votes on acceptance towards the overall IEQ and the four environmental aspects, namely thermal environment, IAQ, visual environment and aural environment, collected in this study. Votes made in the previous study are shown for comparison.[8] According to the table, 32 out of 52 (62%) residents in this study were satisfied (voted '1') with the overall IEQ in their homes while 166 out of 175 (95%) residents in the previous study showed satisfaction. Regarding the four environmental aspects, satisfaction votes were similarly much lower in this study. A significantly different voting pattern was observed in this study (p<0.0001, Chi-square test).

Table 1. Votes on IEQ acceptance

Environment	**Overall IEQ**		**Thermal environment**		**IAQ**		**Visual environment**		**Aural environment**	
vote	0	1	0	1	0	1	0	1	0	1
This study	20	32	25	27	28	24	18	34	20	32
Residential buildings[8]	9	166	13	112	7	118	10	115	12	113

Table 2 presents the measurement results of both previous study on average residential buildings in Hong Kong and current study on very small residential units.[8] Variations of the measured data over the 15-min measurement period were generally small which is good to serve the purpose of this study. The PMV index[15] was determined using four environmental parameters (i.e. T_a, T_r, V_a and RH) and two occupant parameters (clothing value I_{cl} and metabolic rate M_e). This study showed significant differences between the group of unsatisfied residents and the group of satisfied residents in a number of parameters for thermal environment, i.e. *PMV*, T_a, T_r and T_o (p<0.05, *t*-test), indicating the residents were sensitive to thermal comfort.

Results between the two studies were compared and the *t*-test results are exhibited in Table 2. As no significant differences were found in all average temperatures (i.e. T_a, T_r and T_o) and the average horizontal illuminance levels, the thermal and visual environments of both studies were comparable. It can be seen from the table that although the significantly higher *PMV* in this study can be associated with the higher metabolic rate and thus the lower clothing value (for thermal comfort), the *PMV* differences between voting groups are insignificant.

Some very small units in this study had no airy or openable windows and thus poorly natural-ventilated. It also noted for the height differences of SDUs would be reduced from original apartments by 0.15–0.2m (for additional water supply and drainage piping), which was insignificant as compared with the mandatory minimum height (2.5 m) for habitable rooms in Hong Kong. No significant trend of CO_2 levels was recorded during the measurement period in SDUs and thus the ventilation condition was considered steady. Insignificant effect of room volume for the measured CO_2 level was therefore assumed. As a result of higher occupancy density (i.e. per capital floor area, surveyed: 5.7 m^2ca^{-1} and average residential: 13.1 m^2ca^{-1}) and poorer ventilation, the average CO_2 level (1,046 ppm) and average air velocity (0.2 ms^{-1}) recorded in this study were significantly higher than the ones reported in the previous study (675 ppm and 0.37 ms^{-1} respectively).[8] In contrast, the average equivalent noise level found in this study was significantly lower than the average reported in the previous study.

Table 2. Indoor environmental parameters for residential buildings

Parameter	Residential buildings[8]	This study	*p*-value, *t*-test
Per capital area (m^2)	13.1	5.7 (3.4)	<0.0001
Predicted mean vote *PMV*	0.27 (0.88)	0.56 (0.82)**	<0.05
Unsatisfied	0.65 (0.95)	0.94 (0.43)	0.43
Satisfied	0.24 (0.86)	0.32 (0.92)	0.65
Air temperature T_a (°C)	27.3 (2.2)	27.4 (2.2)**	0.81
Unsatisfied	28.1 (2.3)	28.3 (1.2)	0.86
Satisfied	27.3 (2.2)	26.9 (2.5)	0.43
Radiant temperature T_r (°C)	27.5 (2.0)	27.3 (1.8)**	0.63
Unsatisfied	28.1 (2.4)	28.2 (1.2)	0.94
Satisfied	27.4 (1.9)	26.8 (2.0)	0.12
Air velocity V_a (ms^{-1})	0.37 (0.2)	0.2 (0.19)	<0.05
Unsatisfied	0.49 (0.3)	0.18 (0.2)	<0.05
Satisfied	0.36 (0.2)	0.21 (0.2)	<0.05
Operative temperature T_o (°C)	27.4 (2.0)	27.3 (2.0)**	0.93
Unsatisfied	28.1 (2.4)	28.2 (1.2)	0.91
Satisfied	27.3 (2.0)	26.9 (2.2)	0.25
Relative humidity *RH* (%)	83.9 (10.5)	73.5 (12.3)	<0.05
Unsatisfied	84.1 (10.3)	76.1 (10.3)	0.09
Satisfied	83.9 (10.4)	71.8 (13.2)	<0.05
Metabolic rate M_e (Met)	1.06 (0.11)	1.13 (0.10)	<0.05
Unsatisfied	1.11 (0.13)	1.15 (0.09)	0.45
Satisfied	1.05 (0.10)	1.12 (0.10)	<0.05
Clothing value I_{cl} (clo)	0.48 (0.11)	0.40 (0.11)	<0.05
Unsatisfied	0.48 (0.11)	0.39 (0.10)	<0.05
Satisfied	0.48 (0.11)	0.41 (0.12)	<0.05
Carbon dioxide ζ_2 (ppm)	675 (328)	1046 (500)	<0.05
Unsatisfied	497 (345)	1240 (609)	<0.05
Satisfied	689 (327)	925 (369)	<0.05
Horizontal illuminance level ζ_3 (lux)	187 (273)	191 (127)	0.88
Unsatisfied	307 (435)	156 (112)	0.36
Satisfied	178 (252)	213 (131)	0.29
Equivalent noise level ζ_4 (dBA)	67.3 (6.2)	62.6 (4.8)	<0.05
Unsatisfied	70.6 (7.9)	62.4 (5.0)	<0.05
Satisfied	67.1 (6.0)	62.8 (4.7)	<0.05

Note: Standard deviation in brackets; *t*-test between satisfied and unsatisfied groups for each indoor environmental parameter, where **: *p*-value ≤ 0.05

Thermal environmental acceptance

With no votes for cold (–3), cool (–2), slightly cool (–1) and warm (2), 18 votes for neutral (0), 8 votes for slightly warm (+1) and 24 votes for hot (+3), this study showed similar results to the previous study: a skew towards the warm side.[8] The results indicate that occupants are willing to pay for a comfortable thermal environment if the thermal environmental parameters are adjustable.

The thermal vote ζ_1 against PMV is given by the following expression (R=0.72, p<0.05, *t*-test),

$$\zeta_1 = 2.79PMV + 0.12; \qquad 0 \le \zeta_1 \le 3 \qquad \ldots (1)$$

Both previous and current studies reported a narrower thermal acceptability range (slopes of 2.2 and 2.79 respectively) than the Fanger's *PMV* model.[8] Besides, the occupants in this study preferred a slightly cool environment as a thermal neutral setting, i.e. $PMV=-0.12$ at $\zeta_1=0$ ($PMV=-0.15$ in the previous study). This outcome suggests that the small unit occupants are more sensitive to hot conditions and tend to be dissatisfied with a hot environment despite its environmental conditions are comparable to the average conditions.

As graphed in Figure 2, the thermal acceptance of a warm environment is skewed to the cool side, indicating a slightly cool environment is preferred. It can be seen that occupants of this study are more sensitive to warmth while having some degree of tolerance to the hot environment ($PMV \ge 2$).

Figure 3(a) illustrates the thermal acceptance δ_1 as a function of operative temperature. This study shows a greater sensitivity to operative temperature change than the previous study. The acceptance is 0.09 for an operative temperature of 32°C, it is much lower than the value of 0.74 for general residential buildings.

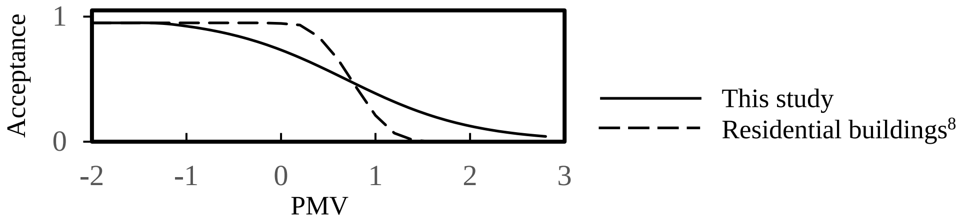

Figure 2. Acceptance of PMV

Acceptance of indoor air quality, visual and aural environments

Figures 3(b)–(d) show the acceptance measurements for CO_2 (δ_2), horizontal illuminance (δ_3) and equivalent noise levels (δ_4). Occupant responses specific to each of these independent factors were record, it is assumed that occupant acceptance of one aspect is solely depends on the surrogate parameter of that aspect. In general, higher level of horizontal illuminance and lower levels of CO_2 and equivalent noise are preferred. Acceptance variability is very small over the ranges of δ_2=0.53–0.22 for CO_2 levels 800–1800 ppm, δ_3=0.62–0.70 for horizontal illuminance levels 10–500 lux, and δ_4=0.66–0.54 for equivalent noise levels 50–80 dBA. The very flat curves of this study in Figures 3(b)–(d) reflect that small unit occupants are more concerned about the thermal aspect and put less emphasis on the other three aspects. Table 3 summarizes the constants for the following regression equation,

$$\delta_0 = 1 - \frac{1}{1+e^{C_{0,0}+\Sigma_i(C_{i,0}\zeta_i)}}; \ \delta_i = 1 - \frac{1}{1+e^{C_{0,i}+C_{1,i}\zeta_i}}; \ i=1,2,\ldots 4 \quad \ldots (2)$$

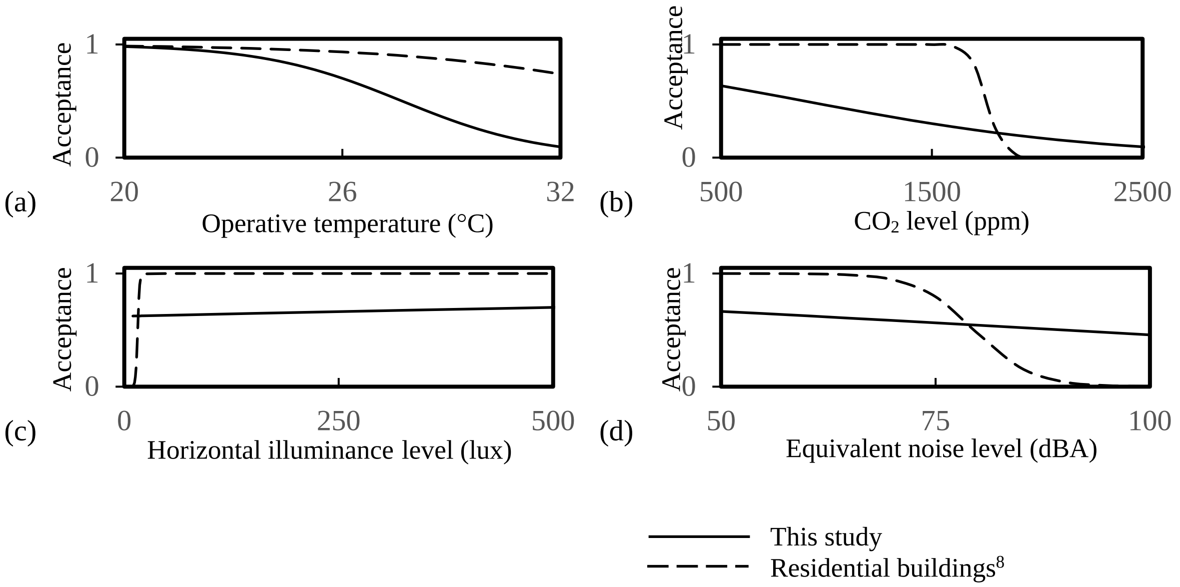

Figure 3. Acceptance of PMV, CO_2 level, horizontal illuminance level and equivalent noise level

Table 3. Regression coefficients

i	Acceptance variable	$C_{0,i}$	$C_{1,i}$	$C_{2,i}$	$C_{3,i}$	$C_{4,i}$
0	IEQ δ_0	–0.0062	0.1710	–0.0140	0.5711	0.2695
1	Operative temperature δ_1	14.3210	–0.5181			
2	CO_2 level δ_2	–0.0014	1.2544			
3	Horizontal illuminance level δ_3	0.0007	0.5001			
4	Equivalent noise level δ_4	–0.0171	1.5466			

Overall indoor environmental quality acceptance

Table 4 exhibits the overall IEQ acceptance values of the two studies under different environmental conditions, i.e. cases *j*. A total of $j = 2^4$, i.e., 16 cases of combinations of contributors δ_i for i = 1,...,4 with binary notation for the acceptance of individual IEQ aspects (i.e. 0 for 'unsatisfied' and 1 for 'satisfied') are presented. The variations of acceptance of assessment aspects $\Delta\delta_i$ are given by Equation (3). Cases with zero samples in both studies were excluded from this calculation.

$$\Delta\delta_i = \sum_{i=1}^{4} \{\delta_0(\delta_i = 1) - \delta_0(\delta_i = 0)\} \quad \ldots (3)$$

Table 4. Overall IEQ acceptance

Case *j*	Contributors				This study		Residential buildings[8]	
	δ_1	δ_2	δ_3	δ_4	Acceptance δ_0	Sample size N_j	Acceptance $\delta_{0,r}$	Sample size $N_{j,r}$
1	0	0	0	0	0.167	6	0	1
2	0	0	0	1	0.2	5	–	0
3	0	0	1	0	0.333	3	0	1
4	0	0	1	1	0.875	8	0.5	2
5	0	1	0	0	0	1	–	0
6	0	1	0	1	–	0	0	1
7	0	1	1	0	0	1	0	2
8	0	1	1	1	1	1	0.833	6
9	1	0	0	0	–	0	0	1
10	1	0	0	1	0	2	–	0
11	1	0	1	0	1	2	–	0
12	1	0	1	1	1	2	1	2
13	1	1	0	0	0	3	–	0
14	1	1	0	1	1	1	1	7
15	1	1	1	0	0.75	4	0.857	7
16	1	1	1	1	1	13	1	95
Total						52		125

Using $\Delta\delta_i$ to indicate the expected acceptance change between the votes 0 and 1 for each environmental aspect, the results as shown in Figure 4 are $\Delta\delta_1$=0.22, $\Delta\delta_2$=0.14, $\Delta\delta_3$=0.43 and $\Delta\delta_4$=0.47 for this study and $\Delta\delta_1$=0.62, $\Delta\delta_2$=0.11, $\Delta\delta_3$=0.28 and $\Delta\delta_4$=0.49 for the previous study, demonstrating insignificant differences in $\Delta\delta_i$ between the two studies (p>0.05, *t*-test), especially for the IAQ and aural aspects (p>0.9, *t*-test). It should be noted that there may be a slight difference in the thermal aspect (p=0.2, *t*-test). The lower value of $\Delta\delta_1$ in this study reveals that the small unit occupants actually feel hot at home.

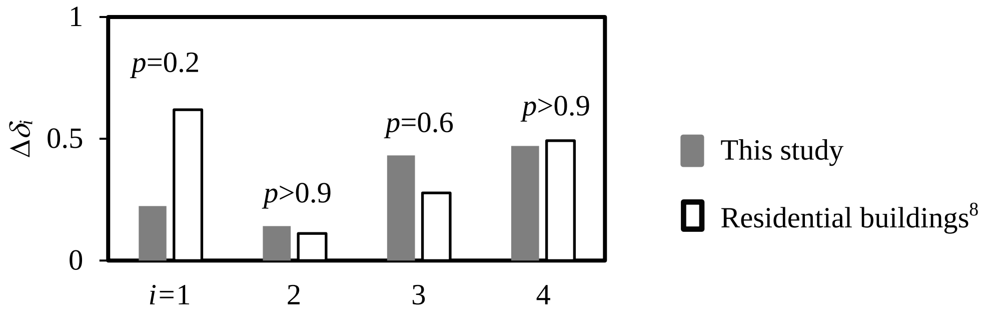

Figure 4. Expected acceptance change of an environmental aspect

The adaptation to reality is also reflected in the environmental cases. Figure 5 shows the overall IEQ acceptance for all cases j when $\Delta\delta_0$=0.1 (unweighted) and $\Delta\delta_{0,w}$=0.04 (weighted by sample size N_j), where $\Delta\delta_0$ and $\Delta\delta_{0,w}$ are quantified by,

$$\Delta\delta_0 = \frac{\sum_j \left(\delta_{0,j} - \delta_{0,r,j}\right)}{16}; \; \Delta\delta_{0,w} = \frac{\sum_j \left(N_j\delta_{0,j} - N_{j,r}\delta_{0,r,j}\right)}{\sum_j \left(N_j + N_{j,r}\right)} \quad \ldots (4)$$

The additional acceptance when $\Delta\delta_0$=0.1 is presented in Figure 6 over some example ranges of parameters ζ_i and acceptances for better, average and poorer scenarios. The difference between the solid line and the dotted line shows an additional tolerance of parameter level by the small unit residents due to their higher tolerance to environmental conditions. Along the two lines, the difference in level varies (for example, 0.04 to 0.11 PMV). The additional acceptance level of the individual aspect gained by $\Delta\delta_0$=0.1 of this study is expected to be higher than that of the previous study as a higher environmental tolerance level is expected among very small space residents (e.g. 0.11 (PMV), 220 ppm, 2 lux and 3.6 dBA versus 0.04 (PMV), 40 ppm, 0.3 lux and 0.4 dBA).

Using the regression coefficients given in Table 3, the overall IEQ acceptance can be expressed by Equation (5). This regression equation is statistically significant (R=0.80, p<0.05, t-test). It gives a narrow predicted acceptance range from 0.47 to 0.75 for $\delta\in[0, 1]$ to reflect not only the hidden occupant responses (no significant overall trend) against individual environmental parameters for CO_2, horizontal illuminance and equivalent noise levels but also the occupant adaptation to the reality of a hot environment.

$$\delta_0 = 1 - \frac{1}{1+e^{c_{0,0}+\Sigma_i(c_{i,0}\zeta_i)}};\ i=1,2,\ldots 4 \quad \ldots (5)$$

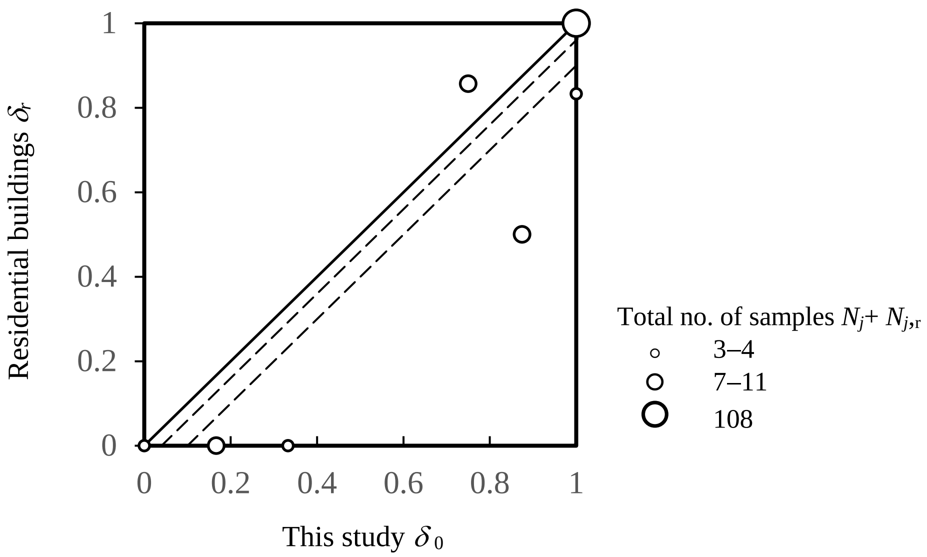

Figure 5. Overall IEQ acceptance

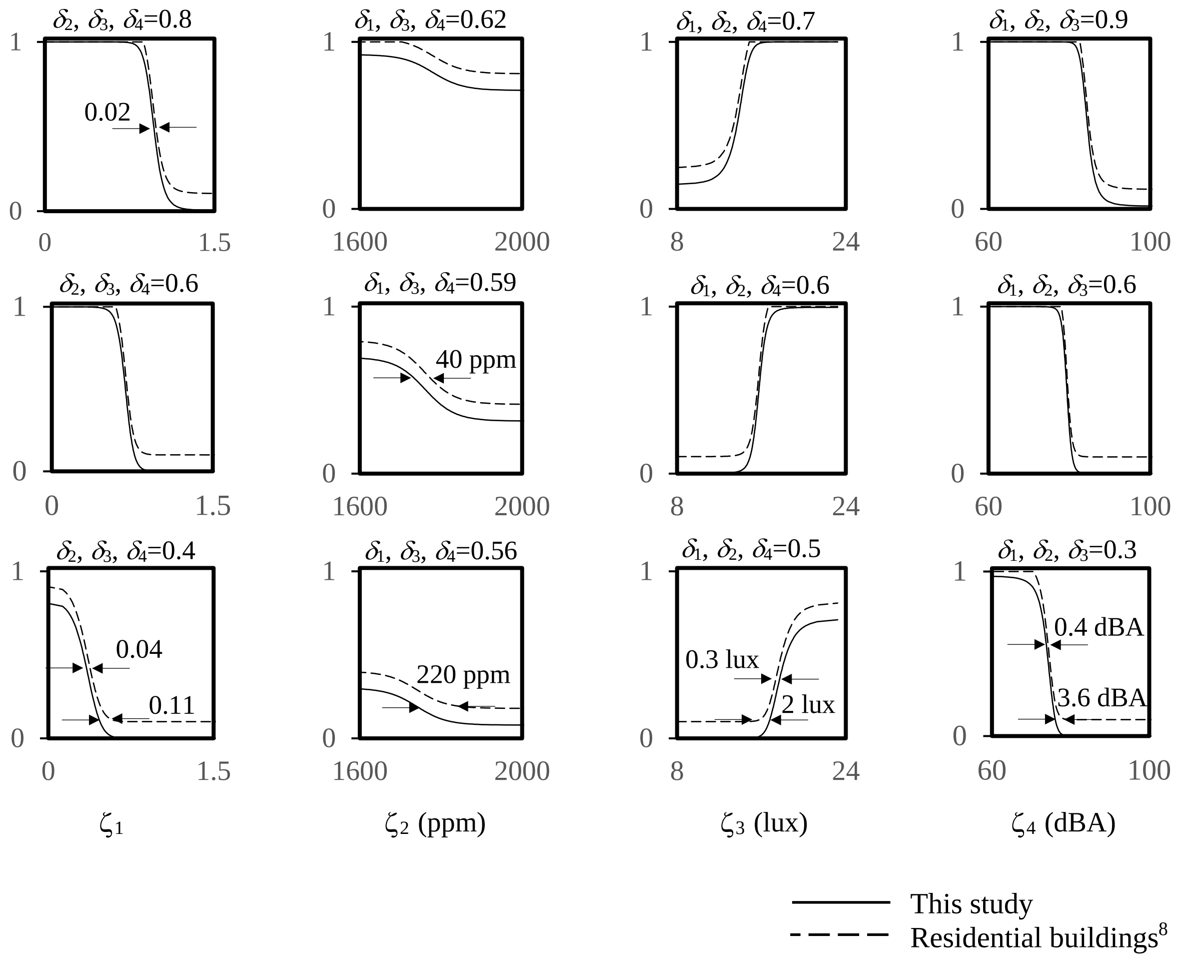

Figure 6. IEQ acceptance shift $\Delta\delta_0 = 0.1$

In order to examine the dependence of the predicted overall IEQ acceptance on the variations of the contributors, example values ζ_2=800 ppm and 1800 ppm, ζ_3=10 lux and 100 lux, and ζ_4=50 dBA and 80 dBA were selected to present an ordinary range of indoor environmental conditions. These conditions were referenced to a study of IEQ acceptance of residential buildings of Hong Kong and used to illustrate the sensitivity of IEQ acceptance in the residential environmen.[8] The values are also within the measurement range in this study. Figure 7 shows the dependency with two contributors unchanged under the selected conditions. As expected, the overall IEQ acceptance predicted for this study is less sensitive to the four IEQ parameters as compared with the average residential buildings. The changes in IEQ acceptance over the operative temperature range (20–32°C) are not significant ($\delta \leq 0.051$), where changes of $\delta \leq 0.5$ were reported for the average residential ones; which is a 10-fold difference.[8]

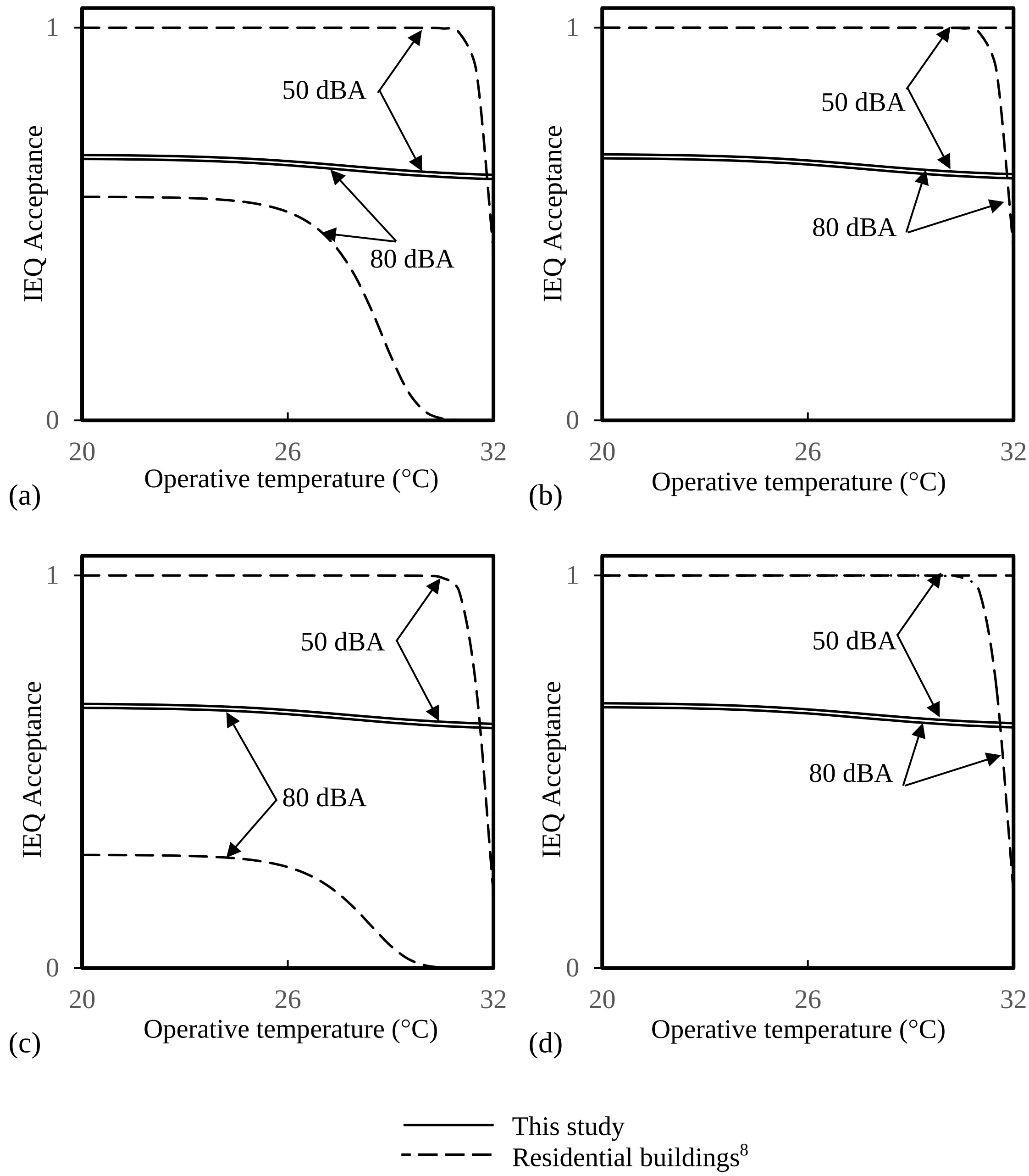

Figure 7. Predicted occupant acceptance of IEQ (a) 800 ppm, 10 lux; (b) 800 ppm, 100 lux; (c) 1800 ppm, 10 lux; (d) 1800 ppm, 100 lux.

Conclusion

This study investigated the IEQ responses from occupants living in very small residential units that are unique to Hong Kong. Through the changes in environmental parameters, including thermal, IAQ, visual and aural, the study demonstrated that the overall IEQ acceptance in these units was different from the one in general residential building environments. Results showed that occupants of these units were more sensitive to warmth and operative temperature change as compared to occupants of general residential buildings. A small variation of thermal acceptance suggested that the small unit occupants had already developed certain degree of tolerance to hot conditions. The adaptation to the reality of a hot environment was also reflected in the overall IEQ acceptance. It is believed that very small space residents have developed tolerance and adaptation to an unchangeable reality, changing environmental conditions does not necessarily alter their acceptance of individual IEQ aspects and overall IEQ.

Acknowledgement

This work was undertaken by the Department of Building Services Engineering, The Hong Kong Polytechnic University. It was partially supported by Hong Kong SKH Lady MacLehose Centre, the Research Grants Council of HKSAR and The Hong Kong Polytechnic University (Project no. 15208817, GYBFN).

Declaration

Mui KW, Tsang TW and Wong LT contributed equally in the preparation of this manuscript. William Yu advised on site measurements.

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