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Indoor environmental quality (IEQ) acceptance of very small flat units of Hong Kong residents

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Abstract

Hong Kong has a challenge of meeting the housing demand due to limited land supply. Recently, some very small residential units have surfaced to accommodate the population expansion in the city. As the extreme environmental conditions in these environment are insufferable to some people, indoor environmental quality (IEQ) responses of occupants living in these units may differ significantly from other field studies on IEQ acceptance in living environments. This study evaluates the IEQ with responses of 52 residents living in very small residential units. Individual acceptance towards IEQ parameters regarding the thermal, indoor air, visual and aural environment and overall IEQ are analyzed. In general, most of the IEQ parameters are comparable to data collected in average residential buildings. Regarding the thermal response, a narrower thermal acceptability range in this study shows a greater sensitivity to operative temperature change. A small variation in thermal acceptance indicates that the occupants have already developed tolerance to the hot indoor environment. While for indoor air quality, visual and aural aspects, acceptance variabilities are very small within the measurable range, suggesting that small unit occupants put less emphasis on these three aspects. The study also demonstrates that the overall IEQ acceptance in these units are less sensitive as compared with the average residential environment. Occupants are believed to have developed tolerance and adaptation to an unchangeable reality, which tiny changes of environmental conditions make no significant influence to their acceptances of individual IEQ aspects and overall IEQ.

Keywords: indoor environmental quality (IEQ), very small residential units, sensitivity, acceptability, tolerance

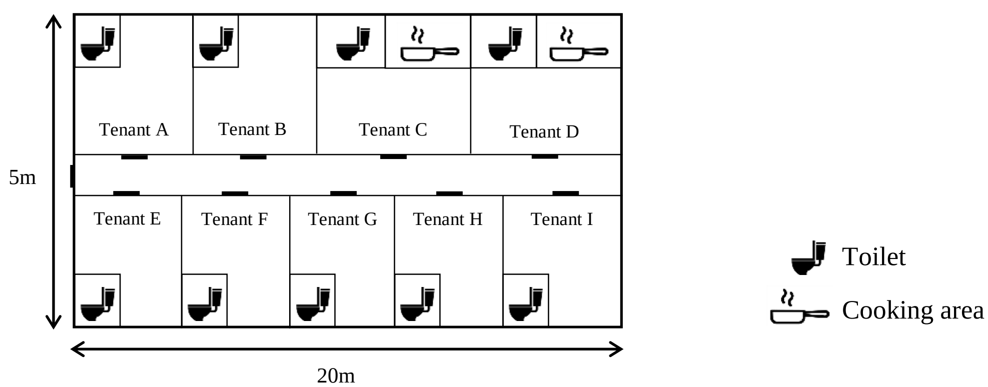
1. Introduction

Hong Kong is one of the most populated places in the world. With a population density of 6,733 people per km^2, she has been facing a housing shortage for years probably due to limited land supply (Census and Statistics Department, 2018). Recently some very small living spaces high in occupancy density and poor in environmental conditions have appeared in housing market, providing the underprivileged an alternative and affordable choice of accommodation (Transport and Housing Bureau, 2013; Lai, Lee & Yu, 2016). These spaces come in different forms and sizes without a standard, but in general they can be sub-categorized into temporary shelters, rooftop structures, cocklofts, bed-spaces (a bunk in shared quarters) and subdivided units (SDUs) (Legislative Council Secretariat, 2013). It has been reported in a regional survey that an estimation of 209,700 people were residing in 92,700 SDUs in 2016 (Census and Statistics Department, 2016).

According to the above survey, the median floor area of these units was 10 m^2 (7–13 m^2), with the average per capita living area of 5.3 m^2 ca^{-1}, which is much 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}) (The Centre of Land Resource and Housing Policy, 2015).

These units are created by constructing additional wall structures and openings in regular flats. In most of the SDUs, household facilities like toilet and kitchen are lacked/ shared among several sub-units. Alternatively, some may be equipped with private toilet and independent cooking space. Figure 1 shows some examples of typical SDUs (Census and Statistics Department, 2016).

Figure 1. Example arrangement of subdivided units



Occupant's comfort to the environment can be affected by various factors. Physical parameters like air temperature, air quality, sound level, visual environment, etc. can influence one's perspective to the overall environment. Other occupant–related factors like lifestyle, demographic factors, social status, expectation, etc. are also found to have impacts on occupant's IEQ (Al Horr et al., 2016; Bluyssen, Aries and van Dommelen, 2011). Since the IEQ contributing factors interrelate with each other, IEQ is worthwhile to be addressed by an integrated approach than individually.

Multivariate-logistic regression models were proposed for several typical indoor environments to assess IEQ (Cao et al., 2012; Wong, Mui & Hui, 2008; Lai et al., 2009). These models related IEQ into four indoor aspects, namely thermal comfort, IAQ, visual and aural environment, into a 2–fold process. Responses towards individual aspects and overall IEQ are evaluated through a two-fold logistic regression analysis. A multivariate-logistic regression model for residential apartment in Hong Kong was proposed to approximate the overall IEQ acceptance with respect to the four above-mentioned aspects, which can be used as a quantitative evaluation criterion for similar living environments (Lai et al., 2009).

It can be seen the development of housing in Hong Kong is tending to become smaller in foreseeable future. As extreme living conditions are uncomfortable to some people, resident's perception to the environment may affect their judgements on IEQ. While it has been known that high occupancy may intensify the negative feelings towards the environmental conditions, inconsistency may appear when IEQ responses from the residents of these units are compared with data from average residential buildings. As increasing number of small units are expected in the future, in hope of extending our understanding on IEQ responses to residential environment, this study investigates the IEQ responses from occupants living in very small residential units and compares the data with average residential environment.

2. Methodology

Field survey was carried out in small residential units in Hong Kong from October to December 2016, which was the autumn/ winter period.

On-site measurement of physical environmental parameters included 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. T_a, T_r, V_a and RH were used to compute operative temperature (T_o) and predicted mean vote (PMV), which is one of the most recognized thermal comfort models for assessing thermal comfort based on a steady-state heat balance model and experiment results (Fanger, 1970). CO_2 is a surrogate indicator for ventilation which is considered as representative for IAQ evaluation. Both horizontal illuminance and equivalent noise levels are known to be indicators for the visual and aural environments. Since the surveyed units were mostly small without any partitioning, a 15-minute physical measurement was considered indicative to represent a 'steady' environmental state which occupants were responding to.

In addition to objective (physical) measurement, subjective IEQ assessments were carried out to evaluate occupant's comfort responses to environmental conditions. The interviewees were asked a set of questions regarding the perceived IEQ. Their thermal sensations (ζ_1) were evaluated by voting with a seven-point semantic differential scale: cold (–3), cool (–2), slightly cool (–1), neutral (0), slightly warm (+1), warm (+2) and hot (+3) (ANSI/ASHRAE, 2010; Fanger, 1970). A five-point scale with 'very good', 'good', 'neutral', 'bad' and 'very bad' was used to assess their IAQ acceptances (ζ_2). A maximum of 100 points were also awarded by occupants for evaluating their aural comfort (ζ_3) and visual comfort (ζ_4).

To ensure consistency of 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 for validation. For example, ζ_1=–3/–2/+2/+3 were 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 responses contradict and it would be regarded as invalid. For aural and visual comfort, extreme cases (e.g. an acceptable visual environment with a score of 0) would be considered to be invalid. An overall IEQ acceptance by interviewee was collected at last. During the interview, occupant's clothing value and metabolic rate were determined based on ASHRAE Standard 55 (ANSI/ASHRAE, 2010).

3. Results

3.1 Physical measurement

A total of 52 sets of objective and subjective measurements were collected from residents residing in 8 single units, 37 SDUs, 1 in bedspace unit and 6 rooftop houses. Single units and rooftop houses were comparatively larger in size with a floor area of 18.6 to 37.2 m^2; while the SDUs and bedspace were much smaller with a floor area of 6.0 to 18.6 m^2. The average per capita floor area is 5.7 m^2ca^{-1} (ranging from 2.3 to 16.3 m^2ca^{-1}), which has no significant difference (p>0.05, Z-test) than the one reported (Census and Statistics Department, 2016), but significantly lower than (p<0.0001, t-test) the average living space in Hong Kong (Hong Kong Housing Authority, 2016).

Table 1 exhibits the acceptance votes on individual IEQ aspects and overall IEQ by the occupants of surveyed small units and by residents from average residential buildings (Lai et al. 2009). It is noteworthy that in this study, only about one-third of residents were satisfied (voted '1') with overall IEQ; 95% residents living in residential buildings voted satisfied instead. Satisfaction votes in individual aspects were of similar case too, suggesting significantly different voting patterns in all four IEQ aspects as well as the overall IEQ in this study than the previous one (p <0.0001, Chi-square test).

Table 1. Acceptance votes on individual IEQ aspects and overall IEQ

Environment	**Overall IEQ**		**Thermal comfort**		**IAQ**		**Visual comfort**		**Aural comfort**	
Vote	0	1	0	1	0	1	0	1	0	1
This study (n = 52)	20	32	25	27	28	24	18	34	20	32
Residential buildings (n= 175) (Lai et al., 2009)	9	166	13	112	7	118	10	115	12	113

Remarks: 1 - Satisfied; 0 – Unsatisfied

Table 2 presents the measurement results of selected IEQ parameters in this study with comparison to the previous study in residential buildings (Lai et al., 2009). Both studies adopted the same 15-min measurement protocol, therefore direct comparison can be carried out to evaluate the difference in environmental conditions between very small residential units and average residential buildings in Hong Kong. During the measurement, fluctuation of the levels were small that it could be considered as "steady" and suitable for IEQ assessment.

Significant differences were observed in a number of thermal comfort parameters and PMV (as indicated with **; p-value <0.05, t-test) between satisfied and unsatisfied group in this study suggested that residents of very small residential units were sensitive to thermal comfort, while such differences were not seen in average residential buildings.

Results between the two studies were compared by t-test. No significant differences were found in temperature and horizontal illuminance levels suggested similar thermal and visual environments. It is noteworthy that significantly low V_a were recorded in this study, which may be explained by the fact that these units were constructed by partitioning regular flats, which the sub-divided units might not (most likely) have openable windows, therefore poorly ventilation were resulted. This explanation is also supported by an elevated level of CO_2 in these units compared to average residential buildings, due to poor ventilation and high occupancy density. On the other hand, the average equivalent noise levels in these units were significantly lower than the average residential buildings, suggesting a better aural environment.

Table 2. Measurement results of IEQ parameters

Parameter	**Residential buildings (Lai et al., 2009)**	**This study**	***p*-value, *t*-test**
Per capita 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

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

3.2 Thermal comfort acceptance

18 votes for neutral (0), 8 for slightly warm (+1) and 24 for hot (+3) were recorded in this study, suggesting a skew toward the warm side in thermal comfort sensation by the occupants. A similar pattern of thermal sensation was also found in previous study (Lai et al. 2009). Thermal comfort votes were used to correlate with PMV index by Fanger. The result is shown in Equation 1.

$\zeta_1 = 2.79\text{PMV}+0.12; \quad 0 \leq \zeta_1 \leq 3; \quad (R = 0.72, p < 0.05, t\text{-test})$ … (1)

It can be seen that the thermal acceptability range is narrower than suggested by Fanger (as indicated by a slope > 1 in Equation 1, shown in Figure 2). In addition, the occupants in this study preferred a slightly cool environment than thermal neutral setting. This suggests that the occupants in this study are more sensitive to hot environment than occupants in average residential buildings, and tend to be dissatisfied with it, despite that the thermal conditions are comparable in the two types of units concerned.

Figure 3(a) showcases the thermal acceptance of the two studies. It suggests that acceptance leans towards the cool side in current study with a wider range of thermal condition than in average residential buildings. It can be concluded that occupants in small units are more sensitive to warmth but have developed tolerance to the hot environment. Figure 3(b) illustrates the thermal acceptance as a function of operative temperature. A greater sensitivity to operative temperature than the previous study was found. At the highest measurable range of operative temperature, acceptance in very small unit is as low as 0.09, on the other hand, acceptance of 0.74 is estimated for general residential buildings.

Figure 2. Measured and predicted thermal sensation votes

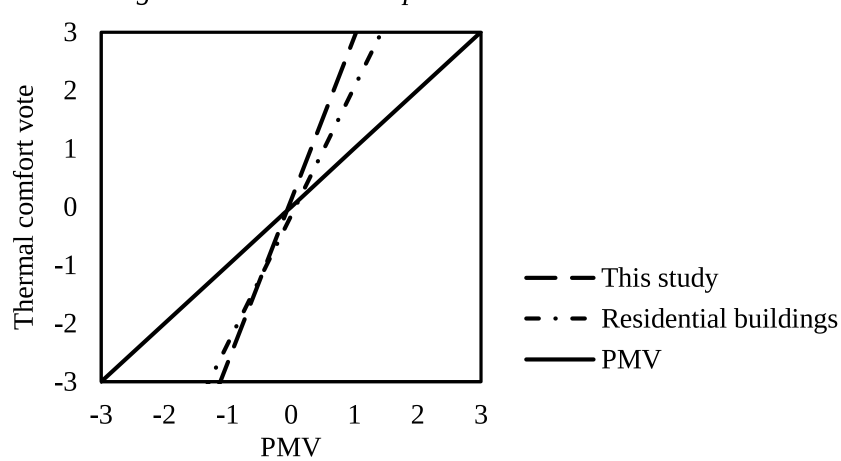
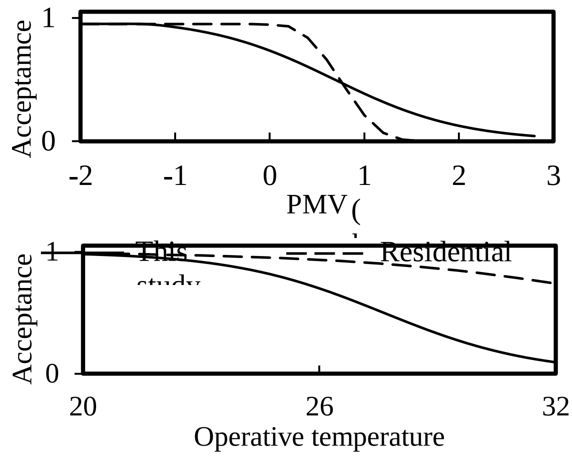


Figure 3. Plot of thermal acceptance against (a) PMV; and (b) Operative temperature



3.3 IAQ, Visual and Aural comfort acceptance

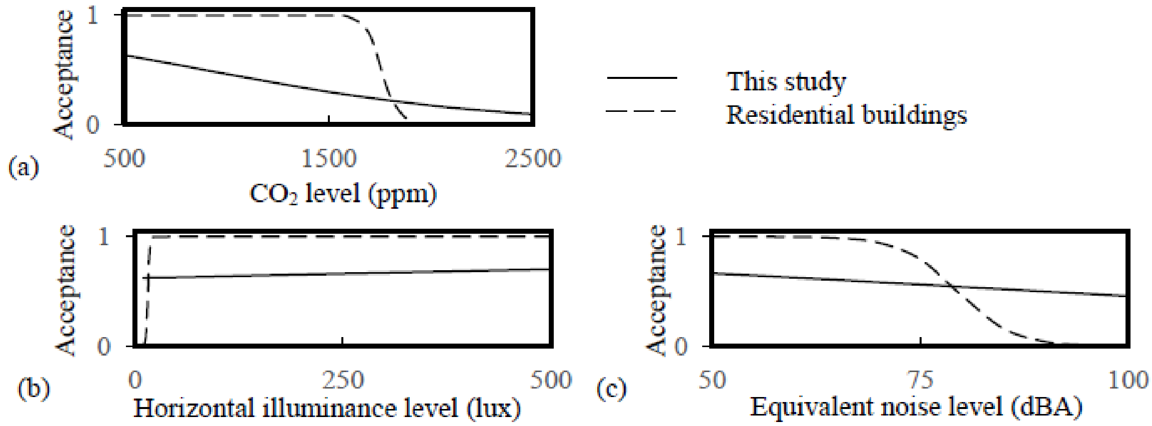
Assuming that occupant's acceptance in one environmental aspect solely depends on the surrogate parameter, i.e. IAQ depends on CO_2 level, visual comfort depends on horizontal illuminance level, aural comfort depends on equivalent noise level, plots of acceptances against levels of parameter in the three aspects are presented in Figure 4. In summary, occupants prefer low CO_2 and sound level, and high level of illuminance level, but the variability is small as shown by flat curves along measurable range. The results suggest occupants might be largely influenced by their own perceptions to the environment instead of environmental variation. Occupants also pay more focus on thermal comfort rather than the other three aspects. In addition, regression analysis was done to correlate overall IEQ acceptance with the 4 aspects. Given in Equation 2, the resulting coefficient constants are summarized in Table 2.

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

Table 2. 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			

Figure 4. Plot of (a) IAQ; (b) Visual comfort; and (c) Aural comfort acceptance



3.4 Overall IEQ acceptance

Table 4 shows the overall IEQ acceptance values of the two studies under different environmental conditions. 16 cases of combinations of contributors δ_i for i = 1,...,4 with binary notation for thermal, IAQ, visual and aural acceptance are presented.

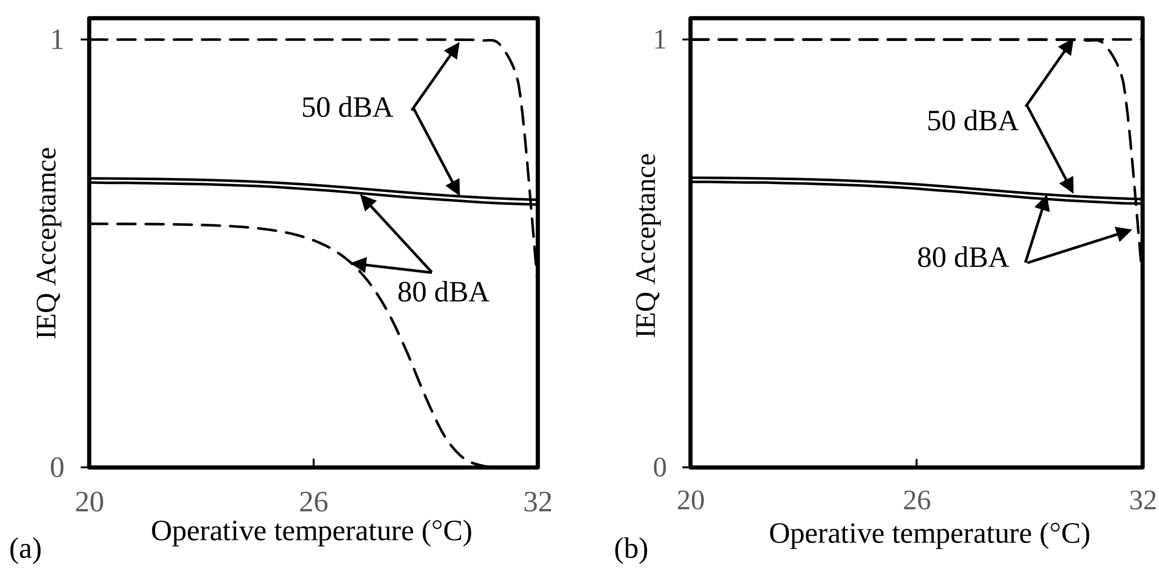
Figure 3. Overall IEQ acceptance under different environmental conditions

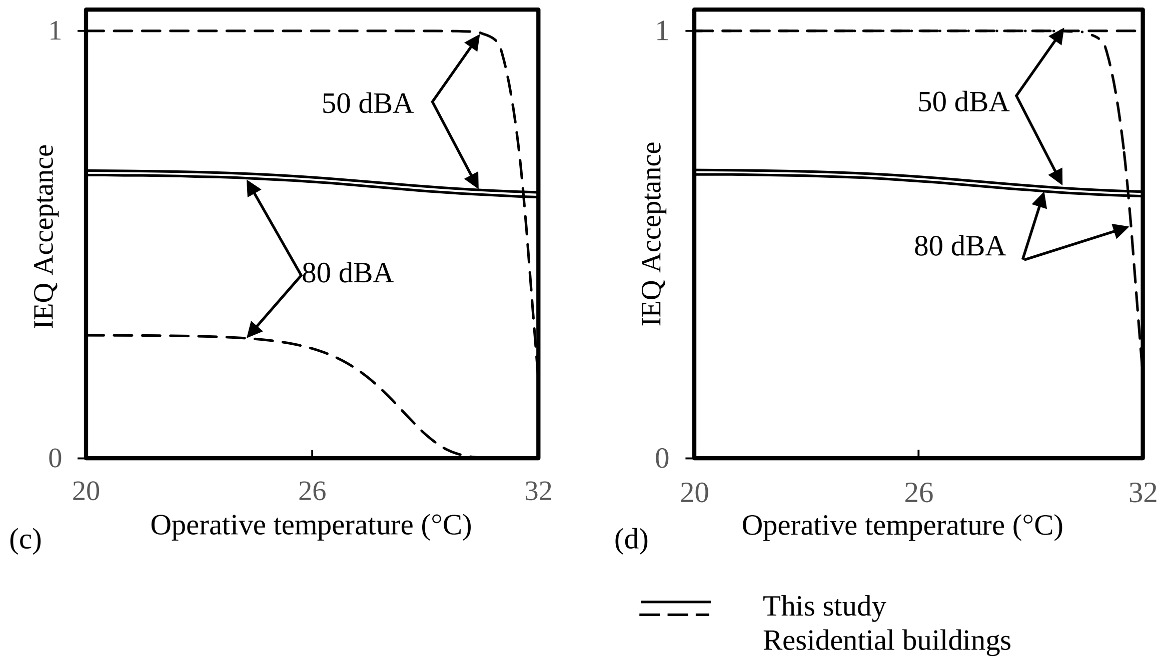
Case *j*	**Contributors**				**This study**		**Residential buildings**	
	δ_1	δ_2	δ_3	δ_4	**Acceptance** δ_0	**Sample size** N_j	**Acceptance** $\delta_{0,r}$	**Sample size** $N_{j,r}$
1	0	0	0	0	0.167	6	0	1
2	0	0	0	1	0.2	5	–	0
3	0	0	1	0	0.333	3	0	1
4	0	0	1	1	0.875	8	0.5	2
5	0	1	0	0	0	1	–	0
6	0	1	0	1	–	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

Results of regression analysis are shown above in Table 2 in previous session. It is found to be statistically significant (R = 0.80, p <0.05, t-test). Narrow range for predicted acceptance from 0.47 to 0.75 is resulted for $\delta \in [0, 1]$, which reflects occupant's responses against individual environmental parameters as well as occupant's adaptation to the reality of a hot environment.

The dependence of predicted overall IEQ acceptance on the variations of the contributors was explored. Exemplary cases with ζ_2 = 800 ppm and 1800 ppm, ζ_3 = 10 lux and 100 lux, and ζ_4 = 50 dBA and 80 dBA were selected which could be found in typical indoor environments. Figure 5 displays such dependency relationship with two fixed contributors. As expected, subtle changes are observed for this study compare to average residential buildings with changing environmental conditions. The changes in IEQ acceptance over the operative temperature range (20 − 32°C) are not significant ($\delta \leq 0.051$), where changes of $\delta \leq 0.5$ (about 10 folds) were reported in average residential buildings. The results suggest occupants of these small units are not sensitive to variation in environment condition.

Figure 5. Predicted IEQ acceptance with varying operative temperature under selected environmental conditions: (a) 800 ppm, 10 lux; (b) 800 ppm, 100 lux; (c) 1800 ppm, 10 lux; (d) 1800 ppm, 100 lux





Conclusion

This study investigates the IEQ responses from 52 residents living in very small residential units. It was found that overall IEQ acceptances collected from these units were significantly different from those in average residential buildings, even though the average environmental conditions of the two indoor spaces were considerably similar. Results suggested that occupants of small units are more sensitive to operative temperature than other IEQ parameters. However, small variation in thermal acceptance suggested that they had already developed some kind of thermal tolerance to high temperature. Adaptation to the environment was also reflected in the overall IEQ acceptance. Occupants in small unit had already developed a perception to the spaces regardless the actual environmental conditions. Changing environmental condition might not necessarily change the occupant's acceptance to individual IEQ aspects and overall IEQ. Environmental conditions become a lesser concern to them compared to residents living in average houses.

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