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Student learning performance and indoor environmental quality (IEQ) in air-conditioned university teaching rooms

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Abstract

This study investigates the relationship between Indoor Environmental Quality (IEQ) and learning performance in air-conditioned university teaching rooms via subjective assessment and objective measurement. Together with the data of air temperature, relative humidity, air speed, mean radiant temperature, CO_2 concentration, equivalent sound pressure level, horizontal illumination level, occupant activity and clothing insulation level measured in four classrooms and four large lecture halls, self-reported learning performance (in calculating, reading, understanding and typing) and perceived IEQ are evaluated. The results show strong associations of the overall IEQ votes with the environmental parameters. While thermal comfort, indoor air quality and visual environment are of comparable importance, aural environment is the major determining factor. The study also reveals that all IEQ complaints have similar impact on learning performance and there is a good correlation between learning performance and the number of complaints. To aid design needs, empirical expressions that approximate the impact of unsatisfactory IEQ on learning performance loss are proposed.

Keywords

Indoor Environmental Quality (IEQ); learning performance; classroom and lecture hall; subjective and objective measurement

Nomenclature

$C_{0,0}$ and $C_{i,0}$	regression constants
C_L	clothing value (clo)
C_{op}	constant for air velocity
GM	geometric mean
GSD	geometric standard deviation
max, min	maximum of and minimum of
M_e	metabolic rate (met)
n_{ij}	non-zero count
n_{ieq}	expected probable number of IEQ complaints
N	sample size
$N_{\phi_0=1}$	acceptance count
R	correlation coefficient
R_h	relative humidity (%)
SD	standard deviation
T_a	indoor air temperature (°C)
T_{op}	operative temperature (°C)
T_r	mean radiant temperature (°C)
V_a	air velocity (ms^{-1})

Greek letters

ϕ_0	overall IEQ acceptance
ϕ_i	occupant acceptance
ϕ_1	thermal environment acceptance
ϕ_2	IAQ acceptance

ϕ_3	visual environment acceptance
ϕ_4	aural environment acceptance
γ	PMV index
ζ_1	thermal sensation vote
ζ_2	CO_2 concentration (ppm)
ζ_3	horizontal illumination level (lux)
ζ_4	equivalent sound pressure level (dBA)
ζ_5	background noise level (dBA)
ξ	deviation ratio
ρ	learning performance loss

Subscripts

j	of case j
o	of observed value
p	of predicted value

1. Introduction

Occupant acceptance of an environment depends on a number of environmental parameters. Four basic components, namely thermal comfort, indoor air quality (IAQ), aural and visual comforts, are identified for determining an acceptable indoor environmental quality (IEQ) [1,2]. Despite a growing amount of IEQ studies, the impact of IEQ on student learning performance in air-conditioned classrooms is still lacking [2,3].

Ventilation plays a major role in maintaining thermal comfort and IAQ. A school IEQ investigation reported that 64% of the tested classrooms did not satisfy the thermal comfort conditions, and inadequate ventilation in some classrooms resulted in high carbon dioxide (CO_2) concentrations [4]. Another study suggested that schools should not only assess the functioning of air-conditioning equipment, but also evaluate the ventilation rate and sound level ensemble [5]. Although there are improved air-conditioning systems and recommended energy saving strategies for ventilated classrooms, due to the complex interaction among indoor environmental parameters, a more concrete guidance on environmental performance for schools is required [5-7].

In Hong Kong, university teaching rooms are served by central air-conditioning systems and students adjust to the prevailing indoor environmental conditions chiefly by the choice of clothing and activities. This study measured the latent occupant acceptances of thermal comfort, IAQ, visual and aural levels in some university teaching rooms and correlated the results with self-reported learning performance. Based on the assumption that an occupant always prefers certain environmental conditions in an indoor space (i.e. a binary latent response), this study extended an earlier proposed IEQ model from offices to university teaching rooms [1]. The overall IEQ acceptance measured was used to calculate the model constants.

The overall IEQ acceptance ϕ_0 can be expressed by a multivariate logistic regression model as shown in Equation (1), where $C_{0,0}$ and $C_{i,0}$ are the regression constants which can be determined from the field measurement data, and for i=1,…,4, ϕ_i are the occupant acceptances that correlate with the thermal sensation vote ζ_1, the CO_2 concentration ζ_2 (ppm), the horizontal illumination level ζ_3 (lux), and the equivalent sound pressure level ζ_4 (dBA) respectively [1].

$$\phi_0 = 1 - \frac{1}{1 + \exp\left(C_{0,0} + \sum_{i=1}^{4} C_{i,0}\phi_i(\zeta_i) \right)} \quad (1)$$

The thermal environment acceptance $\phi_1(\zeta_1)$ is given in Equation (2), where $C_{0,1}$ and $C_{1,1}$ are the regression coefficients and the maximum acceptance is 0.95 [8],

$$\phi_1 = 0.95\exp\left[-\left(C_{0,1}\zeta_1^2 + C_{1,1}\zeta_1^4\right)\right] \tag{2}$$

With regression coefficients $C_{0,j}$ and $C_{1,j}$, the acceptances $\phi_2(\zeta_2)$, $\phi_3(\zeta_3)$ and $\phi_4(\zeta_4)$ are described by the following logistic regression models,

$$\phi_j = 1 - \frac{1}{1+\exp\left(C_{0,j} + C_{1,j}\,\zeta_j\right)};\ j = 2,\ldots,4 \tag{3}$$

The expected probable number of IEQ complaints n_{ieq} is determined by,

$$n_{ieq} = \sum_{j=1}^{4}\left(1-\phi_j\right) \tag{4}$$

2. Methodology

All measurements were conducted at The Hong Kong Polytechnic University, where the total campus area for teaching activities was 93,500 m^2 and could accommodate 28,000 students. General teaching activities were scheduled from 8:30 am to 10:30 pm Monday to Friday and some activities were arranged on Saturday from 8:30 am to 5:30 pm. Data including booking time, class size, floor area and nominal room capacity for one academic year were retrieved from the university room booking system for investigation [9,10]. Preliminary occupant load assessments (by actual counting on an hourly basis throughout the day) against the booking records were made to ensure sufficient respondents.

The IEQ study covered lectures delivered by professors of the same department in eight teaching rooms: four 60-seat classrooms C1 to C4 and four 140-seat lecture halls H1 to H4 (floor areas ranged from 91 to 166 m^2). The average number of occupants per unit floor area was 0.74 m^{-2} (standard deviation SD=0.14 m^{-2}). All experiments were carried out on weekday evenings (Monday to Thursday, 6:30 to 10:00 pm) in a 3-month period.

During each lecture, which was 3 hours long with a break of about 20 minutes, air temperature (range = 0 to 50°C; accuracy = ±0.6°C; resolution = 0.1°C; response time = 120 seconds), globe temperature (range = −37 to 45°C; accuracy = ±0.5°C; response time = 3.8 minutes), relative humidity (range = 5 to 95%; accuracy = ±3%; resolution = 0.1%; response time = 20 seconds), air velocity (accuracy = ±3% over the range 0.05-2 ms^{-1}; response time = 0.2 seconds), CO_2 concentration (range = 0 to 5000ppm; accuracy = ±(50 ppm + 3% of reading); resolution = 1ppm; response time = 20 seconds), illumination level (accuracy = ±2% over the range 50-2000 lux; response time = instantaneous) and equivalent sound pressure level (range = 8 to 12.5kHz; response time = 1 micro second) were measured inside the teaching room every 30 minutes. Outdoor air temperature and relative humidity were also gauged. All instruments were calibrated according to the manufacturer's instructions prior to all measurements; and their specifications met the ASHRAE 55 [11], ISO 7730 [12] and IEC 61672 [13] standards. The Class II field research protocol chosen for this study required the measurement probes to be placed at a point (1 m above the floor) nearest the sitting respondents [14]. Measurement procedures for some IEQ studies were used as references [1,15].

A questionnaire for the subjective assessment of perceived IEQ in terms of four aspects, namely thermal environment, IAQ, illumination and noise levels, was presented to the survey subjects during the lecture break. It included relevant IEQ questions from some previous studies [1,15-18]. Respondents were engineering students attending the same core technical classes and were invited to give comments on their own learning performance. As the occupants had stayed in the lecture for at least an hour when the survey details were explained, they were assumed to be under constant indoor environmental conditions during the survey and supposed to have steady metabolic rates throughout. It should be noted that most of the respondents had their dinner right before class. All questionnaires were collected after the lecture so that interruption to the usual teaching activities was expected minimum.

Semantic differential scale and visual analogue scale are common tools used in the subjective evaluation of indoor environmental conditions [17-22]. The former is for assessing thermal comfort and IAQ while the latter is for estimating aural and visual comforts. In this study, two IEQ assessment scales, a semantic differential scale r_1 and a dichotomous scale r_2, were employed to form a unified framework to record the occupant responses [1,15]. As a means to evaluate response validity, scale r_1 indicated “Cold, Cool, Slightly Cool, Neutral, Slightly Warm, Warm, Hot” for thermal environment assessment, or “Very Bad, Bad, Less Bad, Neutral, Less Good, Good, Very Good” for IAQ, aural environment, visual environment and overall IEQ assessments. Scale r_2 gave direct feedback via the question: “Is the thermal environment/indoor air quality/noise level/illumination level/indoor environmental quality acceptable to you?”, and two ranks: “(1) Acceptable” and “(0) Unacceptable”. The ratings from scale r_2 were used to determine the model parameters in Equations (1) to (4).

There was another semantic differential scale r_3 for self-reported learning performance. Four learning-related activities, i.e. calculating, reading, understanding and typing (minimal thinking required), were evaluated. The performance rating scale was from the minimum to the maximum in percentage values: 0%, 15%, 30%, 50%, 70%, 85% and 100%. Respondents were not restricted to fill in a percentage that best described their own performance. Confirmation questions about the influence and improvement of IEQ in relation to the learning performance were asked for checking response consistency.

3. Results

Table 1 summarizes the environmental conditions of the surveyed teaching rooms in terms of indoor air temperature T_a (°C), mean radiant temperature T_r (°C), relative humidity R_h (%), air velocity V_a (ms^{-1}), CO_2 concentration ζ_2 (ppm), horizontal illumination level ζ_3 (lux), equivalent sound pressure level ζ_4 (dBA), and operative temperature T_{op} (°C) which can be calculated using the following, where C_{op} is a constant for the air velocity V_a [11],

$$T_{op} = C_{op} T_a + \left(1 - C_{op}\right) T_r \,; \quad C_{op} = \begin{cases} 0.5 & ; V_a < 0.2 \\ 0.6 & ; 0.2 \le V_a < 0.6 \\ 0.7 & ; 0.6 \le V_a \end{cases} \qquad (5)$$

All of the above parameters were assumed normally distributed ($p>0.95$, Shapiro-Wilk test), and postulated steady as no significant trend was found over the teaching period ($p>0.05$, t-test). The environmental conditions were continuously monitored after each lecture and showed no significant changes between different measurement sessions ($p>0.05$, t-test), except for the operative temperature of classroom C3 ($p=0.03$, t-test). It was noted that the measured air velocities were higher than those found in some Hong Kong air-conditioned offices, and thus a higher contribution of indoor air temperature T_a to the operative temperature T_{op} [23]. Moreover, the equivalent sound pressure levels were significantly higher than the background noise levels in all teaching rooms ($p<0.01$, t-test) except the lecture hall H3 and classrooms C2 and C3 ($p<0.05$, t-test).

A total of 340 questionnaires, among which 28 were incomplete and excluded from subsequent analysis, were collected and the overall responding rate was about 50%. The 312 valid respondents (26% female and 74% male) were in the age range of 18-55: around 80% aged 21-30, and 18% aged above 30. Grouped under acceptable IEQ and unacceptable IEQ, their statistical clothing value C_L (clo) and metabolic rate M_e (met) data are presented in Table 2. The recorded clothing values varied due to central air conditioning. Normality was assumed (p>0.95, Shapiro-Wilk test) for mean radiant temperature T_r, operative temperature T_{op} and horizontal illumination level ζ_3. Except for air speed V_a, horizontal illumination level ζ_3 and equivalent sound pressure level ζ_4, significant differences were reported between acceptable and unacceptable IEQs ($p \le 0.05$, t-test).

As neither the lecturers nor the lecture materials were recorded, their influences on student learning performance were not examined.

3.1 Thermal comfort

The survey results revealed that 84% of the 312 respondents were satisfied with thermal comfort, 76% with IAQ, 91% with the visual environment and 90% with the aural environment. As the occupants had little control over some thermal comfort parameters including air temperature, relative humidity, mean radiant temperature, local air speeds and ventilation, they expressed significant concerns about the control of thermal comfort and IAQ.

The dichotomous assessment showed that 261 respondents accepted the thermal environment. For the thermal sensation votes ζ_1, a seven-point semantic differential scale from −3 to +3 indicating the feelings of cold, cool, slightly cool, neutral, slightly warm, warm and hot respectively was used. 1.5% of the occupants voted for cold (−3), 6% for cool (−2), 29% for slightly cool (−1), 47% for neutral (0), 12% for slightly warm (+1), 3% for warm (+2) and 1.5% for hot (+3). The thermal sensation votes were skewed towards the cool side (i.e. 16.5% for $\zeta_1 > 0$ vs 36.5% for $\zeta_1 < 0$) and that was consistent with the results found in local office and residential buildings [15,16,24]. 88% of the votes were in the range $-1 \le \zeta_1 \le +1$. Slightly lower than the neutral operative temperature of 23.6°C (SD=1.1°C) observed in some Hong Kong air-conditioned offices, the average operative temperature of the surveyed environments was 22.2°C (SD=1.6°C) [16].

Figure 1 illustrates the correlation between the measured thermal sensation votes ζ_1 and PMV index γ [8]. Mathematical expressions of the PMV index, which is a function of air temperature, relative humidity, air velocity, mean radiant temperature, occupant metabolic rate and clothing value (i.e. $\gamma \sim \gamma_{(T_a, R_h, V_a, T_r, M_e, C_L)}$), were briefly reviewed in literature [8,16]. The correlation, with a coefficient R=0.99 ($p<0.0001$, t-test), is given by,

$$\zeta_1 = 5.76\,\gamma + 2.54;\ -3 \le \zeta_1 \le +3 \tag{6}$$

There was no significant difference in the PMV values between genders ($p>0.1$, t-test), except at −1 ($p<0.01$, t-test). Similar to some field studies on direct measurement of thermal acceptability, this study showed a relatively narrower operative temperature range for 80% thermal acceptability than the ones specified in the design guidelines [25]. Reportedly, occupants in air-conditioned offices preferred it ‘slightly cool’. The occupants in this study voted ‘neutral’ instead with an average $\zeta_1=-0.25$.

Interestingly, the PMV values for the teaching rooms were significantly higher than the corresponding values for air-conditioned offices ($p\le0.01$, t-test), and yet significantly lower than the corresponding values for residential apartments ($p\le0.01$, t-test). Generally, thermal comfort is strongly demanded in air-conditioned offices while energy saving is a bigger concern in residential spaces.

3.2 IAQ, visual and aural environments

The measured ranges of CO_2 concentration (501-1665 ppm; geometric mean GM=1065 ppm, geometric standard deviation GSD=316 ppm), horizontal illumination level (218-548 lux; GM=369 lux, GSD=115 lux) and equivalent sound pressure level (57-66 dBA; GM=61.2 dBA, GSD = 2.7 dBA) were assumed normal distributions ($p>0.95$, Shapiro-Wilk test).

Based on the regression coefficients determined from the field measurements, correlations between the occupant acceptance ϕ_i and each of the environmental parameters were studied. As summarized in Table 3, the acceptance votes had statistical significance for IAQ as well as the overall IEQ.

In contrast to thermal comfort and IAQ, the teaching room lighting could be adjusted by the facilitator in order that most occupants (90%) would find the visual environment acceptable for various tasks. Aurally, this study gave a relatively narrow range of equivalent sound pressure levels − 57-66 dBA. Some previous records were 45-70 dBA for air-conditioned offices and 55-83 dBA for construction site offices [17,24]. All teaching rooms were reported to have an equivalent sound pressure level much higher than the background noise level (by 9-23 dBA), except for teaching rooms H3 and C1 (by 5-6 dBA).

3.3 Indoor environmental quality (IEQ)

Association of the overall IEQ acceptance votes with other occupant acceptance votes is exhibited in Table 4 ($p<0.0001$, Chi-square test). The symmetric association for each parameter in the 2 by 2 ($i\times j$) table with non-zero counts n_{ij} can be expressed by Yule's Q value as follows, where $0.5 \leq Q < 0.74$ and $Q \geq 0.75$ indicate moderate and strong relationships respectively [26],

$$Q = \frac{n_{11}n_{22} - n_{21}n_{12}}{n_{11}n_{22} + n_{21}n_{12}} \qquad (7)$$

The Q values for the thermal environment votes, IAQ votes, visual environment votes and aural environment votes were 0.76, 0.68, 0.75 and 0.88 respectively, demonstrating moderate to strong associations with the overall IEQ votes. Table 3 shows the relative sensitivity of each contributor ϕ_i (i.e. thermal, IAQ, visual and aural) to the overall IEQ ϕ_0, − a larger value means a greater sensitivity to unit change within the measurement range. The thermal (1.162), IAQ (0.963) and visual (1.077) coefficient values were comparable and suggested similar sensitivity. With a coefficient value almost double (1.993), the aural environment was found to be a relatively sensitive contributor.

By taking the binary notation for the acceptance (i.e. 0=Unacceptable and 1=Acceptable) to rank the four contributors ϕ_i in the order from the most important to the least (a total of 2^4 possibilities as listed in Table 5), the observed overall IEQ acceptance ϕ_0 of case j is expressed in Equation (8). The relationship between the predicted and observed IEQ results for all cases is illustrated in Figure 2, with error bars determined by 1/N.

$$\phi_{0,j} = \left(\frac{N_{\phi_0=1}}{N}\right)_j ; \; j = 1,\ldots,16 \tag{8}$$

The number of respondents who accepted the indoor environment was 195. From Table 5, cases j=2, 5 and 9 had sample sizes less than 3 and were subject to considerable uncertainty. For all cases of sample size ≥ 3, some agreements were found between the predicted and observed results. There were 9 (out of 13) cases fell within an absolute deviation of ±10% acceptance (i.e. $\phi_0=\pm 0.1$) as demonstrated in Figure 2. A linear association of the predicted and observed overall IEQ acceptances was recommended, with a sample correlation coefficient of 0.61 (p=0.025, t-test) and error bars taken at 1/N.

It was noted that the smaller the sample size, the larger the deviation. Figure 3 pictorializes the deviation ratio ξ against the sample size for each case j given by Equation (9) below, where subscripts o and p indicates the observed and predicted values respectively. According to this figure, the maximum deviation ratio would be 0.1 for a sample size of 47.

$$\xi_j = \frac{\max\left(\phi_{0j,o}, \phi_{0j,p}\right) - \min\left(\phi_{0j,o}, \phi_{0j,p}\right)}{\min\left(\phi_{0j,o}, \phi_{0j,p}\right)} \tag{9}$$

3.4 Learning performance

298 respondents evaluated their own learning performance. Their performance averages for calculating, reading, understanding and typing were 58% (SD=20%), 58% (SD=18%), 60% (SD=18%) and 52% (SD=22%) respectively. There was no significant difference ($p>0.2$, t-test) apart from the significantly lower average for typing ($p<0.05$, t-test).

Table 6 exhibits the learning performance against the expected probable number of IEQ complaints n_{ieq}. Of all 298 respondents, 214, 37 and 11 were not satisfied with one, two and three of the four IEQ aspects respectively, while 8 complained about all four aspects and 28 had no complaints at all.

Figure 4 graphs the learning performance against IEQ improvement requests (i.e. IEQ complaints). In the group of 214 respondents who were not satisfied with one of the four IEQ aspects, there was no significant difference in learning performance among the IEQ aspects ($p\geq0.2$, t-test) except for the aural aspect ($p\leq0.1$, t-test). The median learning performances of respondents expressing dissatisfaction with the aural aspect (N=28) and with the other IEQ aspects (N=34-91) were 65% and 50-55% respectively. Although the measured background noise levels were high (47-57 dBA), no extra concern was reported in terms of number of complaints or learning performance loss as compared with the other IEQ aspects.

For the groups with complaints of 2 or more IEQ aspects, however, no significant difference was observed in the learning performance with or without the aural aspect. All IEQ complaints were therefore assumed to have similar impact on learning performance.

As shown in Figure 5, good correlations were found between the learning performance loss and the number of IEQ complaints n_{ieq} ($p\leq0.005$, t-test). Median performance loss and average performance loss were similar for increased n_{ieq}. The impact of unsatisfactory IEQ on learning performance can be expressed by the relative learning performance loss ρ^*,

$$\rho^{*} = 1 - \frac{\rho(n_{ieq})}{\rho(n_{ieq} = 0)} \tag{10}$$

It was reported that ρ^{*} was about 0.08 per unsatisfactory IEQ aspect.

4. Conclusion

In this study, the relationship between IEQ and learning performance in university teaching rooms was evaluated via subjective assessment and objective measurement. The results showed strong associations of the overall IEQ votes with the environmental parameters. It was also revealed that all IEQ complaints had similar impact on learning performance and there was a good correlation between learning performance and the number of complaints. To aid design needs, empirical expressions for approximating the impact of unsatisfactory IEQ on learning performance loss were proposed.

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Table 1 Indoor environmental quality (IEQ) in surveyed teaching rooms

Place (Dimensions in m)	**Air Temperature T_a (°C)**	**Relative humidity R_h (%)**	**Mean radiant temperature T_r (°C)**	**Air velocity V_a (ms^{-1})**	**Operative temperature T_{op} (°C)**	**CO_2 level ζ_2 (ppm)**	**Horizontal illumination level ζ_3 (lux)**	**Equivalent sound pressure level ζ_4 (dBA)**	**Background noise level ζ_5 (dBA)**
Lecture Hall									
H1 (14×9)	21.5(0.1)	59.5(1.1)	22.8(1.5)	0.61(<0.05)	22.1(0.6)	1048(12)	345(6)	61.0(5.3)	50.6(0.4)
H2 (14×9)	22.5(0.4)	40.2(0.6)	21.8(1.4)	0.42(<0.05)	22.2(0.8)	1007(59)	523(2)	61.0(1.7)	47.3(0.6)
H3 (14×11)	20.5(0.1)	56.3(0.4)	19.6(0.8)	0.53(<0.05)	20.1(0.3)	826(14)	250(4)	57.6(5.1)	52.2(6.1)
H4 (15×8)	19.9(0.2)	64.7(0.8)	20.7(0.6)	0.69(0.14)	20.2(0.3)	492(12)	473(6)	60.1(2.3)	38.5(0.4)
Classroom									
C1 (10×7)	22.8(0.2)	58.5(0.3)	24.7(1.1)	0.50(0.05)	23.5(0.5)	1072(15)	207(17)	57.3(0.6)	51.2(4.2)
C2 (13×9)	25.1(0.4)	71.3(1.3)	24.8(0.5)	0.38(<0.05)	25.0(<0.1)	1627(59)	545(1)	67.0(9.6)	57.3(<0.1)
C3 (12×8)	22.7(0.7)	59.0(1.4)	24.1(0.9)	0.52(0.06)	23.3(0.2)	905(9)	407(13)	61.7(2.3)	52.4(2.8)
C4 (15×9)	21.3(0.1)	64.2(0.4)	21.4(0.8)	0.50(0.06)	21.3(0.3)	1352(58)	338(2)	66.3(1.8)	43.6(0.2)

(Standard deviation SD in brackets)

Table 2 Occupant acceptance of IEQ in teaching rooms

	Parameter									
	T_a (°C)	T_r (°C)	R_h (%)	V_a (ms^{-1})	T_{op} (°C)	ζ_2 (ppm)	ζ_3 (lux)	ζ_4 (dBA)	M_e (met)	C_L (clo)
Acceptable IEQ (N=281)										
Average	22.0	22.3	59.3	0.5	22.1	1053.3	370.8	61.1	1.0	1.3
SD	1.4	1.7	7.8	0.1	1.5	304.9	111.8	2.7	0.0	0.4
Minimum	19.6	19.5	39.8	0.40	19.8	501	218	57.0	1.0	0.54
Maximum	25.1	24.8	70.9	0.80	25.0	1665	548	65.6	1.0	3.56
Unacceptable IEQ (N=31)										
Average	22.6	22.9	63.0	0.5	22.7	1191.4	362.0	61.8	1.0	1.2
SD	1.8	2.0	5.7	0.1	1.8	369.9	138.4	2.9	0.0	0.5
Minimum	19.6	19.5	55.3	0.40	19.8	501	218	57.0	1.0	0.73
Maximum	25.1	24.8	70.9	0.80	25.0	1665	548	65.6	1.0	3.56
p-value (t-test)	0.01	0.03	0.004	0.11	0.01	0.01	0.34	0.09	-	0.39

Table 3 Regression coefficients

i	**Variable**	**$C_{0,i}$**	**$C_{1,i}$**	**$C_{2,i}$**	**$C_{3,i}$**	**$C_{4,i}$**	**Significance, p-value**
0	ϕ_0	−1.697	1.162	0.9629	1.077	1.993	<0.0001
1	ϕ_1	-	0.2179	0.03353	-	-	[a]
2	ϕ_2	3.22	−0.0019	-	-	-	<0.0001
3	ϕ_3	2.13	0.0005	-	-	-	0.77
4	ϕ_4	4.38	−0.0359	-	-	-	0.59

-: not applicable

[a] Coefficients given by [7]

Table 4 Votes on acceptance of perceived IEQ

IEQ	**Votes**	**Thermal ϕ_1**		**IAQ ϕ_2**		**Visual ϕ_3**		**Aural ϕ_4**	
		0	1	0	1	0	1	0	1
ϕ_0=0	31	16	15	18	13	10	21	15	16
ϕ_0=1	281	35	246	58	223	18	263	16	265
Total	312	51	261	76	236	28	284	31	281

Table 5 IEQ acceptance

Case j	Survey samples N	Overall IEQ acceptance ϕ_0	Contributor				Predicted IEQ acceptance ϕ_0
			ϕ_1	ϕ_2	ϕ_3	ϕ_4	
1	5	0.60	0	0	0	0	0.1549
2	2	-	0	0	0	1	0.5735
3	7	0.29	0	0	1	0	0.3498
4	14	0.57	0	0	1	1	0.7979
5	0	-	0	1	0	0	0.3243
6	4	0.75	0	1	0	1	0.7788
7	3	0.67	0	1	1	0	0.5849
8	16	0.94	0	1	1	1	0.9118
9	1	-	1	0	0	0	0.3694
10	5	0.40	1	0	0	1	0.8112
11	3	0.67	1	0	1	0	0.6323
12	39	1.0	1	0	1	1	0.9266
13	5	0.60	1	1	0	0	0.6054
14	6	0.83	1	1	0	1	0.9184
15	7	0.57	1	1	1	0	0.8183
16	195	0.98	1	1	1	1	0.9706

Table 6 Self-reported learning performance

Expected probable number of IEQ complaints n_{ieq}	Sample size N	Learning performance loss ρ (%)				
		Average	Median	SD	Max.	Min.
0	28	62	64	17.5	100	24
1	214	58	55	14.6	100	19
2	37	54	50	15.5	89	26
3	11	47	45	13.5	78	30
4	8	45	43	19.8	73	24

Figure 1: Measured and predicted thermal sensation votes

Figure 2: IEQ acceptance

Figure 3: Deviation ratio of IEQ predictions

Figure 4: Learning performance against IEQ improvement requests

Figure 5: Learning performance

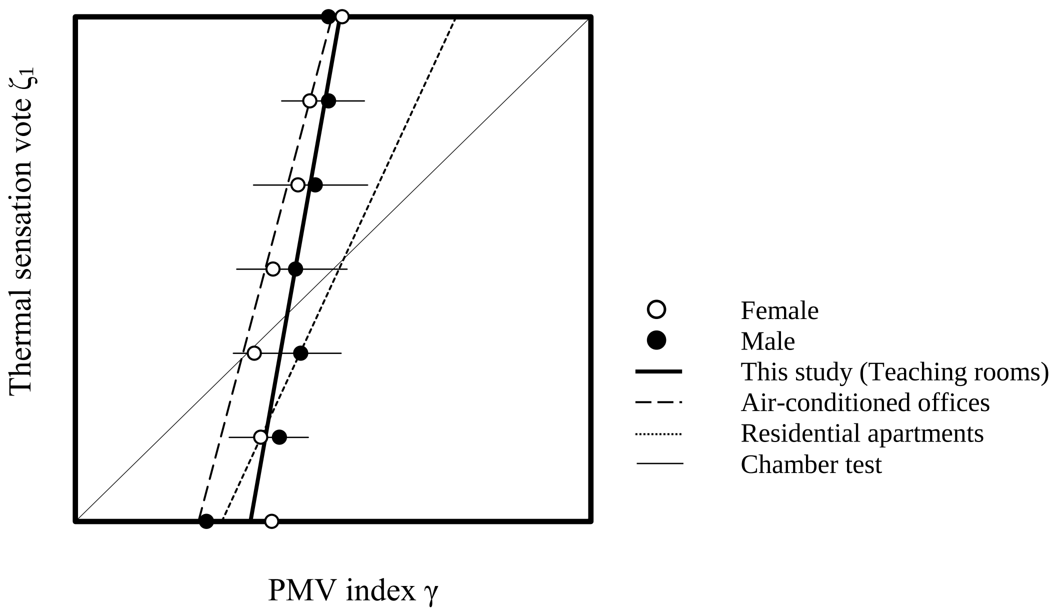

Figure 1: Measured and predicted thermal sensation votes

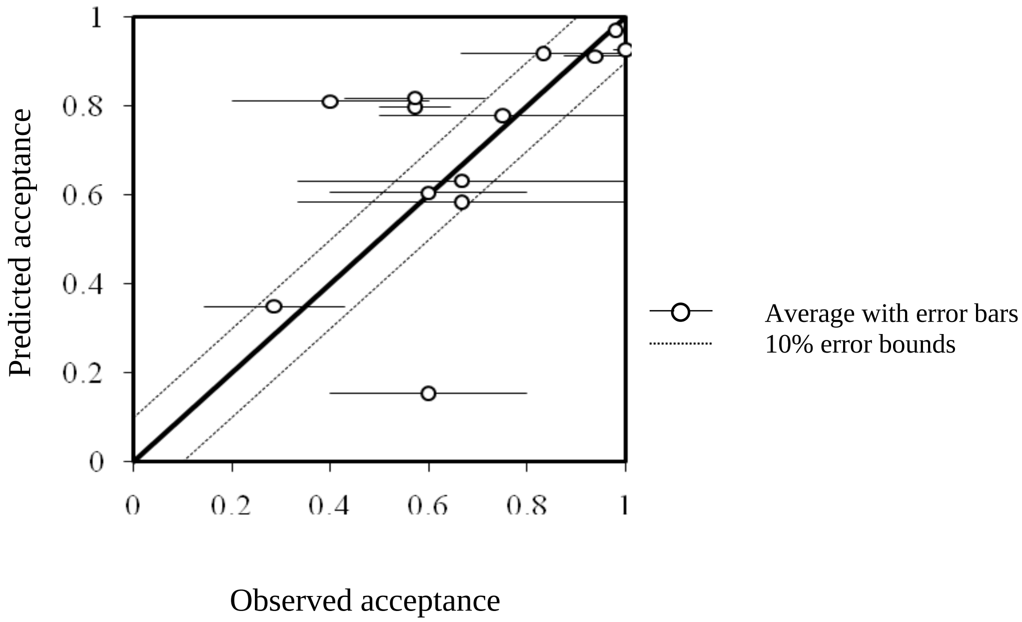

Figure 2: IEQ acceptance

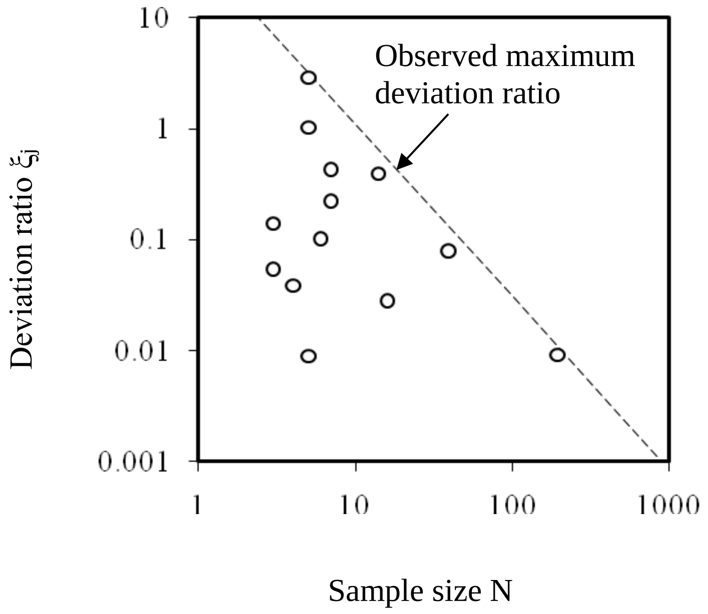

Figure 3: Deviation ratio of IEQ predictions

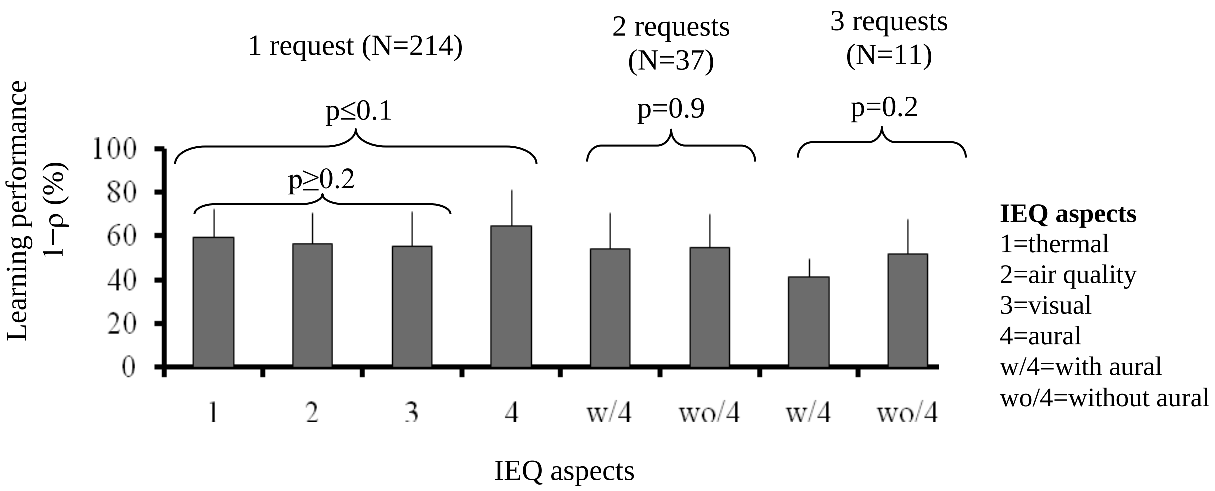

Figure 4: Learning performance against IEQ improvement requests

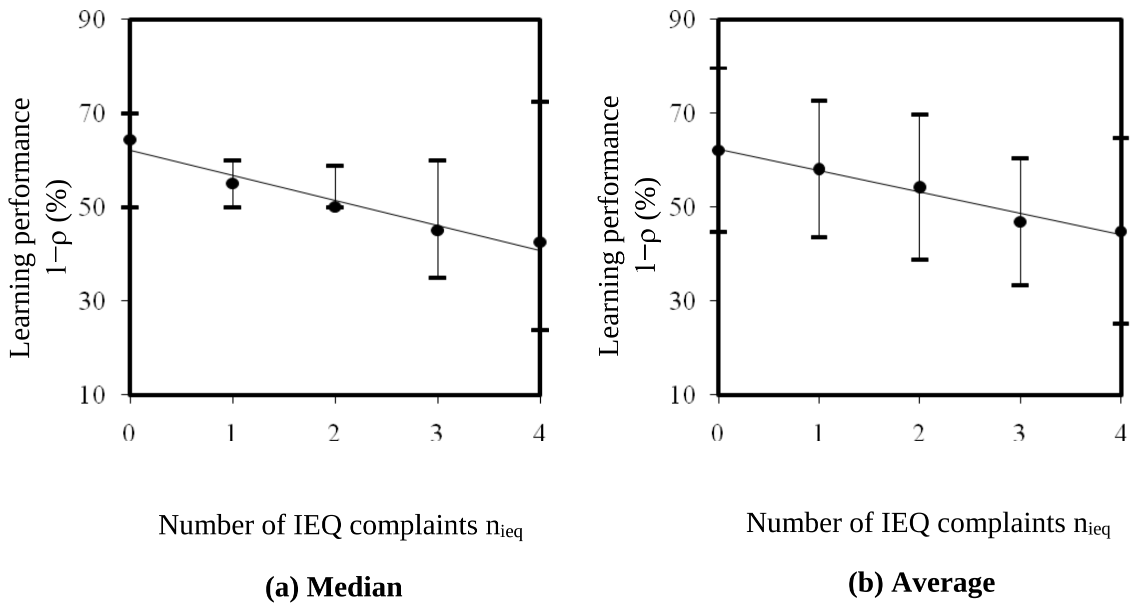

Figure 5: Learning performance