The impact of IEQ in the university lecture theatres on students' concentration levels in London

Abstract

Purpose - University students' lecture theatre concentration levels are significantly related to Indoor Environmental Quality (IEQ). The relationship between IEQ and the self-reported concentration levels of university students was investigated during the winter at University College London (UCL), UK.

Design/methodology/approach A questionnaire survey and physical measurements were utilized to assess the IEQ factors affecting students' concentration levels.

Findings - Lecture theatre design factor was the most significant factor influencing students' concentration levels. And facility environment was more important than thermal environment, indoor air quality, and acoustic environment in influencing students' concentration levels in this winter investigation at UCL, UK. Additionally, students prefer a colder thermal environment. The concentration level of students was positively correlated with the indoor air quality, and negatively correlated with the acoustic environment.

Practical implications - Based on model application, this research could provide lecture theatre IEQ design. This research additionally provides an acceptable indoor thermal environment temperature range based on a large sample, which can be used to calibrate a student performance benchmark.

Originality/value - Since this study evaluates the IEQ factors that influence the concentration levels of university students, interior designers and engineers should consider the rational layout of these factors. Therefore, it may provide a reference for the interior environmental design of lecture theatres in educational buildings.

Keyword Indoor Environmental Quality, facility environment, university student, concentration level

Paper type Research paper

1. Introduction

People living in an urban area will spend approximately 90% of their time indoors (Ganesh *et al*., 2021). For university students, they will spend nearly 30% of their time in the classroom in contemporary society (Paschoalin Filho *et al.*, 2022). A comfortable indoor environment should be designed and provided to satisfy their requirements (Jiao *et al*., 2020; Wang *et al*., 2018). The attainment of healthy settings in classrooms is contingent upon the presence of a high level of indoor environmental quality (IEQ) (Yang and Mak, 2020). According to an analysis of related literature, architects and engineers usually address the design of educational buildings in the same way they do for any other public building (Schwartz *et al*., 2021; Montazami *et al*., 2015). However, IEQ of educational buildings has significant importance for university students. Improving the performance of university students necessitates the provision of a high level IEQ, including optimal thermal comfort (Siqueira et al., 2017; Barbic et al., 2019; Bajc et al., 2019), visual comfort (Serghides et al., 2015), acoustic comfort (Ricciardi and Buratti, 2018), indoor air quality (Papadopoulos et al., 2022) and facility comfort (Yang and Mak, 2020). Numerous studies conducted in air-conditioned and free-running classrooms have indicated that students have expressed significant levels of dissatisfaction with the classroom's predominant environment (Fabozzi and Dama, 2020). When humans are exposed to different temperatures, their bodies will undergo physiological adaptation. The human body's thermoregulatory system maintains a heat balance throughout a broad range of environmental factors, while also allowing for the perception of thermal sensations. According to the thermal adaptation theory, when an individual feels uncomfortable in their surroundings, they would try to make changes in their behaviour, such as using technology or adjusting the environment, in order to obtain a comfortable temperature (Yao et al., 2009). It is noteworthy that this tendency is pervasive not just in developing countries, but also in developed countries (Verso *et al.*, 2021). This is because the reference criteria against which students' comfort is often measured were traditionally created for a steady-state office setting in which clothing and activity levels were assumed to be constant, as was the occupant density in spaces (Ma *et al*., 2021). Additionally, the usage of personal computers and laptops may generate more heat in the classroom. All of these factors lead to a mismatch between the desired and designed indoor environments, as well as poor indoor air quality (Almeida and de Freitas, 2015; Serghides *et al.*, 2015).

Many existing studies confirm that students' concentration levels and learning performance can be influenced by a single aspect of IEQ (Wang et al., 2021; Brink *et al*., 2021; Lee *et al*., 2012). Cho (2017) evaluated the influence of high temperature on students' academic performance and found that high indoor temperature negatively affected their performance. According to the study by Wang *et al.* (2021), students' attention was reported to have statistically significant increases with the improvement of indoor air quality. Franco and Leccese (2020) found that a level of 600–1000 ppm of CO2 concentration is considered optimal in educational buildings like universities. Piderit Moreno and Labarca (2015) developed a climate-based daylight modelling to evaluate the importance of daylight in the performance of the students; they found students' concentration and productivity tend to be improved with the increase area of daylight within the classroom. Knez (2001) conducted a study involving 54 females and 54 males high school students under a constant temperature experimental chamber to explore the influence of light on subjects' cognitive performance, the results showed that females performed better than males in the case of artificial light. In a laboratory study on the relationship between acoustics and students' concentration by Braat-Eggen *et al.* (2021), they found students' concentration distracted significantly by the background sound level when the windows were closed. Research related to a questionnaire involving 542 university students has been studied by Verso et al. (2021), and they found a good correlation with the students' subjective judgements of lighting in the classrooms. However, it was recognised in the 1990s that complaints and health effects associated with IEQ were not driven by a single overriding factor (Papadopoulos *et al.*, 2022). As the main learning space for students during the day, the integrated environment of lecture rooms should not be ignored for its influence on the students' learning performance. Additionally, in comparison with other categories of buildings, universities are considered more vulnerable to environmental problems because recurrent financial shortages lead to insufficient facility management and maintenance (Kim *et al*., 2018).

Several studies investigate the interactive influence of IEQ factors regarding students' concentration (Pellerin and Candas, 2004; Humphreys, 2005; Nimlyat, 2018; Yang and Mak, 2020). Humphreys (2005) conducted interactive research of IEQ parameters on occupant performance by multiple linear regression. He found temperature and air quality are the two most influential factors on employee productivity, with coefficients of 0.39 and 0.36, respectively. Many previous studies have confirmed that the single parameters of IEQ parameters and interactive influence of IEQ parameters on the students' concentration levels and learning performance. There are few combined studies of IEQ parameters as well as facility parameters on students' concentration levels and their learning performance. Therefore, it is necessary to investigate the interactive influences of various factors on students' concentration levels. This research addresses the need by conducting a field survey of 669 university students at University College London (UCL) in London, United Kingdom. The following research objectives were developed for this initiative:

(1) To identify the factors that influence students' self-reported concentration levels based on the factor identification method.

(2) Establish a multiple regression model to obtain the relationship between self-reported concentration level and environmental parameters.

(3) To provide suggestions for future indoor built environment design based on the practical application of the model.

2 Methodology

2.1 Weather data and climate zone in London

The field survey was carried out in London, United Kingdom (51°30 N, 0°39 W). London features a mild oceanic climate with year-round rain and clouds. This makes the city cool in the winter and warm in the summer. The city's average annual temperature was 11.8 °C in 2019. Table 1 shows that the average daily sunlight hours from September to December 2019 were lower than other periods because the average precipitation was high, peaking at 92.8 mm in October.

Table 1. Climate data in London in 2019

Month	January	February	March	April	May	June	July	August	September	October	November	December
Record high (°C)	11.9	20	18	24.4	24.7	33.9	37.2	33.1	26.3	20.9	15.9	13.2
Average high (°C)	7.3	12	12.6	15.2	17.6	21.1	24.7	24.6	20.6	14.9	9.9	9.7
Daily mean (°C)	4.8	7.6	9.2	10.2	13	16.4	19.9	18.9	15.9	11.7	7.3	7.0
Average low (°C)	1.8	3.6	5.5	5.6	8.2	11.9	14.8	14.1	11.6	8.6	4.4	3.9
Record low (°C)	-5.2	-2.7	1.5	-1.2	2.7	8.4	10.4	10.0	6.1	1.2	-2.1	-1.3
Average precipitation mm (inches)	33.2	34.2	49.6	12.8	36	81.8	50.8	33.6	63.0	92.8	74.8	89.6
Average daily sunlight hours (h)	1.8	4.3	3.8	5.7	5.7	5.7	6.3	6.5	5.2	2.4	1.7	1.8

Source: Created by the authors

2.2 Participants and field site

A random sample of 669 healthy UCL students aged over 20 years was selected to participate in the lecture theater survey. The 36 lecture theatres of the buildings selected are all adjacent to the UCL main building in Figure 1. In addition, because the indoor thermal environment can be influenced by the outdoor climate, thereby changing the neutral temperature and adaptive behaviour of occupant, outdoor temperature is also considered as a key factor in terms of thermal comfort (Shooshtarian *et al*., 2020). In this research, the outdoor temperature datasets could be downloaded from Met Office (2021).

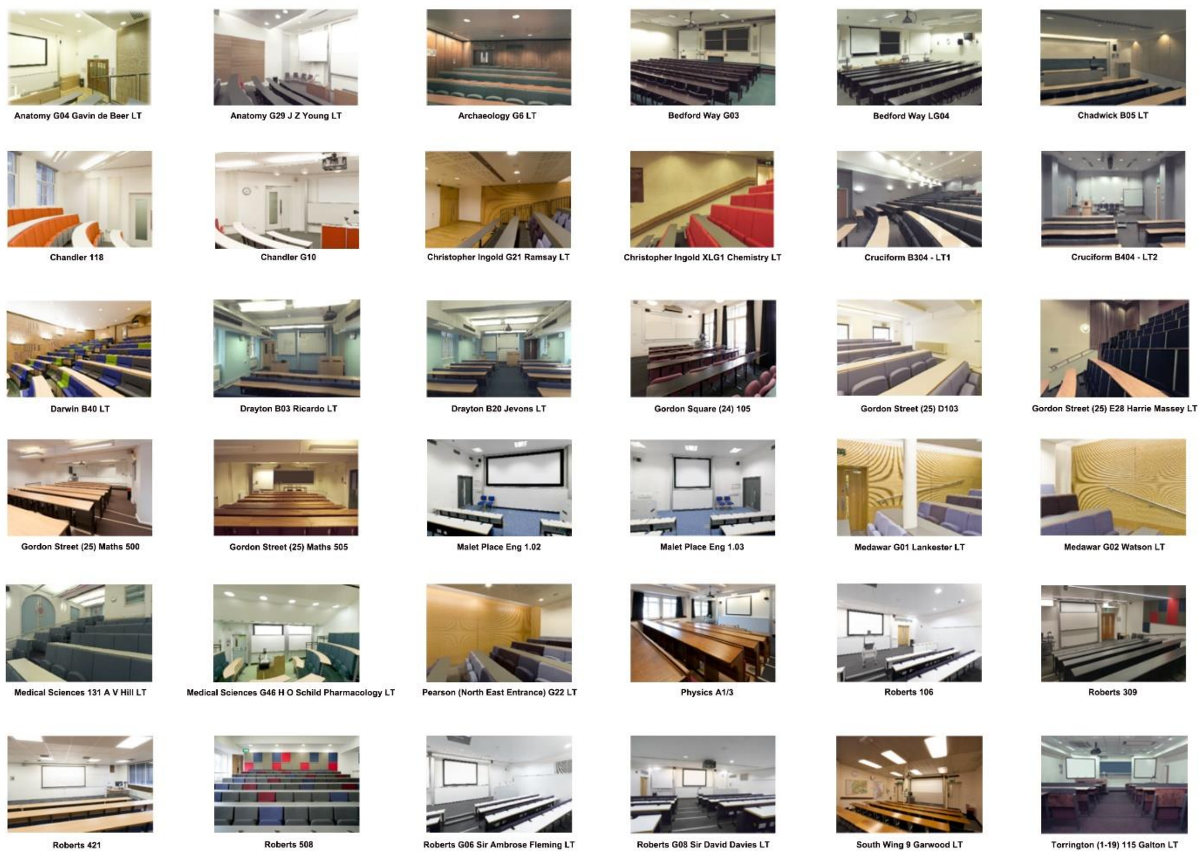

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Figure 1. Site photos of all lecture theatres

2.3 Questionnaire and environmental measurement

Students were distributed questionnaires to collect information on the nine areas indicated below: (1) basic demographics: age, gender; (2) knowledge of the lecture theatres: frequency of lecture theatre attendance and sitting duration; (3) subjective perception in terms of temperature: ASHRAE 7-point scales (−3, −2, −1, 0, +1, +2, +3 indicate cold, cool, slightly cool, neutral, slightly warm, warm, and hot, respectively) and evaluation of the present thermal environment; (4) clothing insulation; (5) subjective sensation of the indoor air: indoor air quality and air movement; (6) subjective evaluation of the concentration level; (7) lighting environment evaluation; (8) acoustic environment evaluation; (9) subjective evaluation of the facility environment. Regarding the evaluation of students' concentration levels, this paper measured them using a five-scale Likert scale in the questionnaire. Each point was given an adjective (1=very dissatisfied, 2=dissatisfied, 3=neither dissatisfied nor satisfied, 4=satisfied, 5=very satisfied). All questions were written in English in Table 2. Additionally, HOBO is the equipment used to simultaneously monitor indoor temperature.

Table 2. Factors relating to indoor environmental quality and questions source

IEQ dimensions	Questionnaire items	Survey questions	Source
Thermal comfort	Temperature	What is your general thermal sensation?	ASHRAE Standard 55
Thermal comfort	Temperature	How satisfied are you with the temperature in your seating space when you are learning?	CBE survey
Air quality	Air quality	How satisfied are you with the air quality in your seating space?	CBE survey
Air quality	Air movement	How satisfied are you with the air movement in your seating space?	CBE survey
Air quality	Air quality	How satisfied are you with the impact of indoor air quality on your concentration level in your seating space?	CBE survey
Lighting quality	Amount of light	How satisfied are you with the amount of light in this lecture theatre?	CBE survey
Lighting quality	Amount of light	How satisfied are you with the amount of light in your seating space?	CBE survey
Lighting quality	Visual comfort	How satisfied are you with visual comfort about the screen in this lecture theatre?	CBE survey

Acoustics quality	Noise level	How satisfied are you with the background noise level in your seating space?	CBE survey
Acoustics quality	Sound level	How satisfied are you with the sound in your seating space (ability to hear the lecturer's voice)?	CBE survey
Layout	Amount of space	How satisfied are you with the facility accessibility in this lecture theatre?	CBE survey
Furnishings	Comfort of furnishing	How satisfied are you with the comfort of this lecture theatre furnishings (chair, desk, computer, equipment, etc.)?	CBE survey
Cleanliness and maintenance	Building maintenance	How satisfied are you with general maintenance of this lecture theatre?	CBE survey
Cleanliness and maintenance	Adjustability of facility	How satisfied are you with your ability to adjust the facilities to meet your needs in this lecture theatre?	CBE survey
Overall satisfaction	Satisfaction with workspace	All things considered, how satisfied are you with this lecture theatre?	CBE survey
Productivity	Concentration level	How satisfied are you with the concentration levels in your seating space?	(Vandergrift et al., 2006)

Source: Created by the authors

Regarding the experimental procedure, when almost the students arrived in the lecture theatre, the experimenter introduced the detailed information of the experimental setup and procedures as well as instructions for completing the questionnaire. The instrument began its operation at the same time (Figure 2). Figure 3 depicts the corresponding flowchart for data collection and analysis. For the indoor thermal environment measurement, the sensor was positioned at the centre of the classroom (Figure 4) and at a height of 1.1 m from the floor (ASHRAE, 2017). This approach to measurement placement is adhered to in all classrooms. Sensor probes for measuring the indoor air temperature were confirmed to meet the ASHRAE 55 standard.

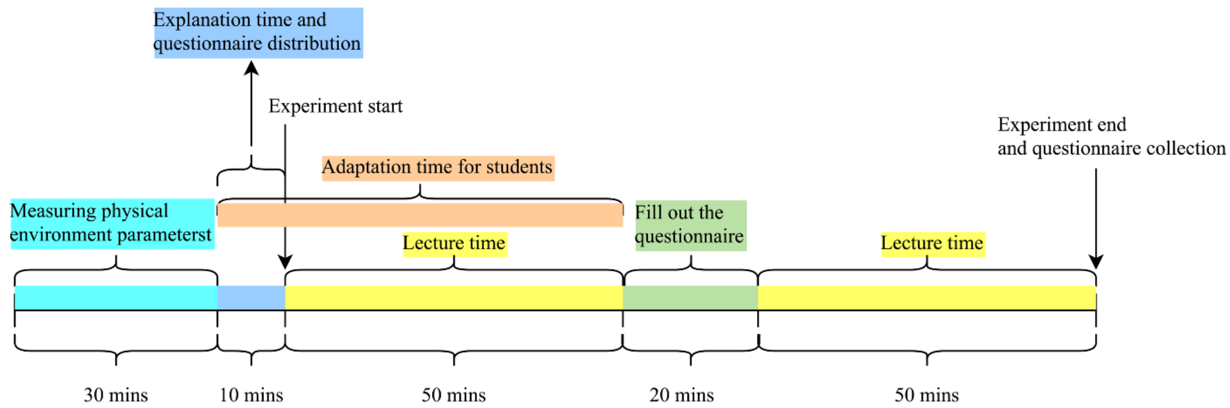

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Figure 2. Experimental procedure

2.4 Statistical analysis

The Statistical Product and Service Solutions (SPSS) 22.0 software was utilised to conduct exploratory factor analysis on the questionnaire data and select indicator variables, so as to construct an indicator framework of the impact of IEQ in the classroom on students' concentration.

2.4.1 Exploratory Factor Analysis (EFA)

Exploratory Factor Analysis (EFA) was conducted on all questionnaires to facilitate the analysis of data sets, summarise their main characteristics, reduce multicollinearities, and consolidate variables into conceptually related and statistically correlated clusters (Flora et al., 2012).

The process of extraction encompassed the use of principal component analysis using the varimax rotation method based on an Eigenvalue greater than 1. Furthermore, we assessed the adequacy of the sample using the Kaiser-Meyer-Olkin (KMO) test (threshold for loading on each factor = 0.5) and evaluated the sphericity of the data using Bartlett's test ($P < 0.01$) (Tabachnick et al., 2013).

2.4.2 Multiple linear regression (MLR)

Additionally, multiple linear regressions (MLR) were employed in this study, which is a kind of regression method that examines the association between a single response variable (dependent variable) as well as two or more controlled factors (independent variables). In terms of the procedure of developing a forecasting model of students' concentration levels in MLR, the stepwise regression model was applied in SPSS. The approach of stepwise regression combines forward selection and backward elimination. This model refers to Minitab Methods and Formulas to add and delete controlled variables as required (Ghani and Ahmad, 2010).

2.5 Variable selection and software

Five factors, including thermal environment, air quality, acoustic environment, light environment, and facility environment, were used as IEQ factors to evaluate college students' concentration levels. Fifteen indexes including thermal comfort votes, air movement (local) and light quality (local) et al. were selected as the second-level indicators. A recapitulation of our available second-level input indicator was given in Table 3, along with an abbreviation for each variable and a symbol for use in the table of experimental results.

In this study, we established a multiple linear regression model with the students' concentration level as the dependent variable and the second-level variables of thermal environment, indoor air quality, acoustic environment, lighting environment and facility environment as the independent variables. The equation of this model is as follows:

$$Y_i = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k + \mu_i \quad (1)$$

where, Y_i is students' concentration level, β_0, β_1, …, β_k are regression coefficients, X_1, X_2, …, X_k are the independent variable, μi is random variable.

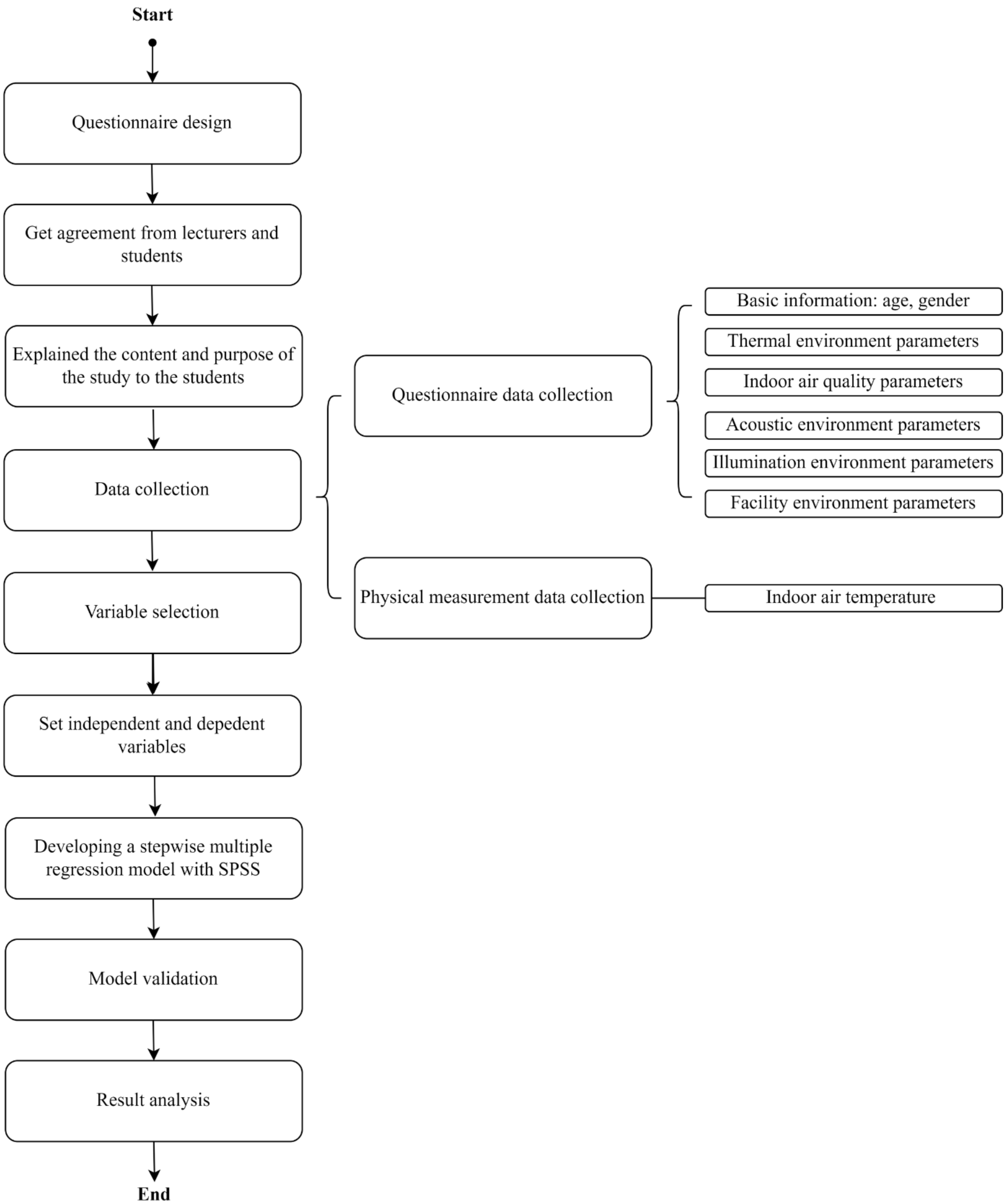

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Figure 3. Procedure for obtaining data and results analysis

3 Results

3.1 Reliability analysis of questionnaires

The internal consistency of all questions in the questionnaires obtained with Cronbach's alpha indicated 0.63, which suggested an internal consistency of the questionnaire. In addition, Churchill (1973) proposes that a Cronbach's alpha coefficient of 0.6 is acceptable.

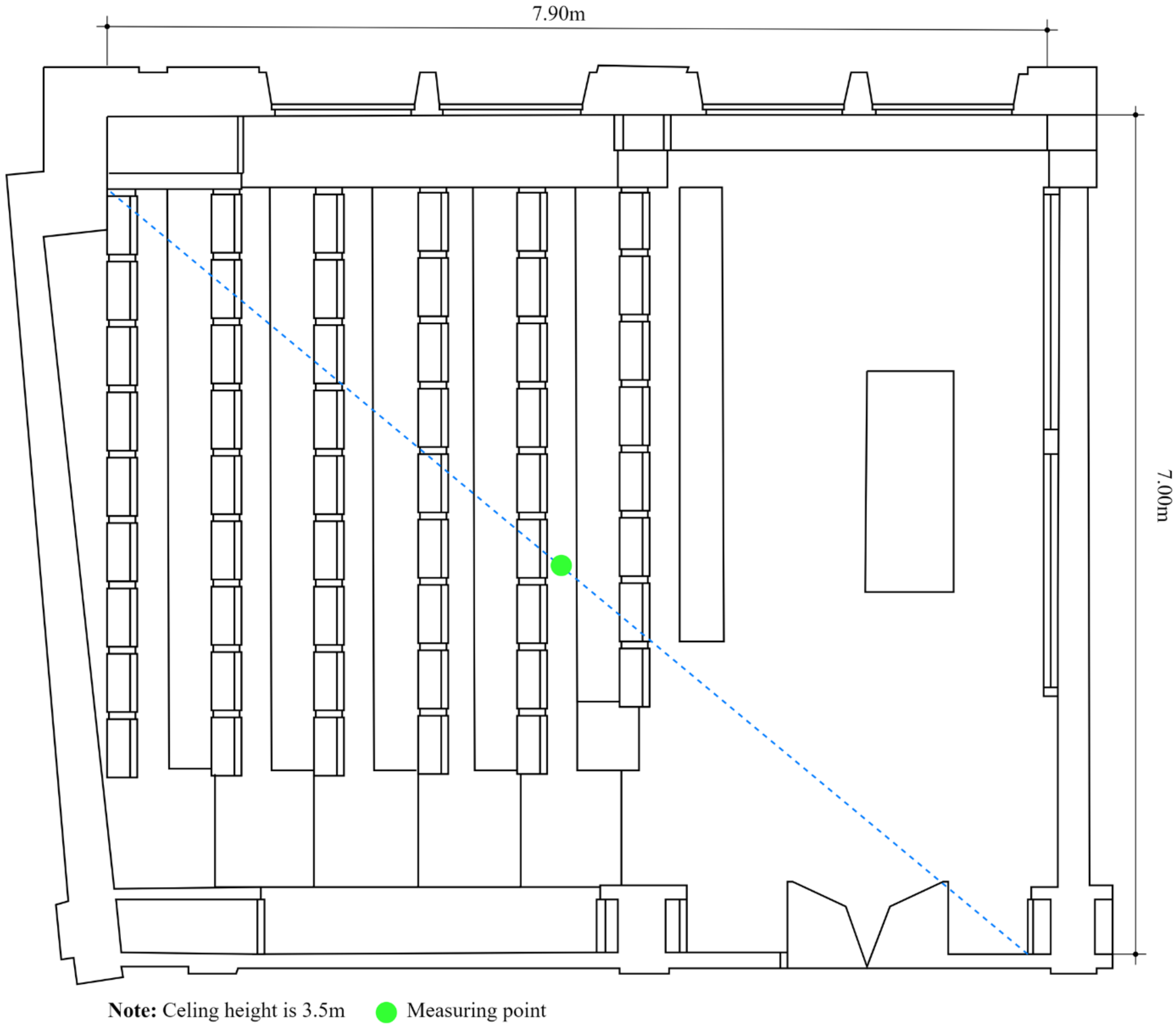

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Figure 4. Measuring sensor location in the classroom

3.2 Exploratory factor analysis

The determination of the number of factors and the magnitude of factor loadings was conducted via the use of EFA. The analysis used principal component extraction as a method to identify the factors. The scree plot, in combination with the KMO and Bartlett sphericity tests, were calculated. Values > 0.50 characterise good sampling adequacy. The Bartlett's sphericity test revealed a statistically significant result ($p < .05$) in Table 4, indicating that the EFA is appropriate for the analysis. All of the items satisfied the requirements for EFA. The analysis yielded five factors that explained 60.794 % of the variance of the data in Table 5.

The first factor was labelled "Facility Environment" and includes items referring to the evaluation perceived in the class on the indoor physical facility environment. The second factor, "Thermal Environment", includes evaluations perceived from indoor air temperature and related factors affecting indoor air temperature and indoor air quality items. The third factor was labelled "Lighting Environment," and it includes an evaluation of artificial light and natural light perceived by students in the class. The fourth factor, "Acoustic Environment", refers to how the students perceive an assessment of the lecturer's voice and background noise. Finally, the fifth factor, "Air Quality (concentration)," deals with items that affect students' assessment of the impact of indoor air quality on their concentration levels. It can be noted that the first factor, "Facility environment", stands out compared to the others as it explains almost 20% of the variation of the data.

Table 3. Indicators of the influence of the indoor environment on students' concentration level

Target variable	First-level variable	Second-level variable	Description	Variable symbol
Students' concentration level	Thermal environment	Thermal comfort scale	Thermal sensation vote (ASHRAE seven-point scale)	X_1
		Thermal comfort for learning	Participants' evaluation of the current thermal scenario learning environment	X_2
	Indoor air quality	Air movment (local)	Participants' evaluation of indoor air movement of their seating position	X_3
		Air quality (local)	Participants' evaluation of indoor air quality of their seating position	X_4
		Air quality (concentration)	Participants' evaluation of the impact of indoor air quality on concentration level	X_5
	Acoustic environment	Acoustic (background)	Participants' evaluation of the acoustics of their seating position	X_6
		Acoustic (lecturer)	Participant's acoustics evaluation of the lecturer	X_7
	Lighting environment	Lighting quality (lcoal)	Participants' evaluation of lighting quality of their seating position	X_8
		Lighting quality (general)	Participants' evaluation of lighting quality in their lecture theatre	X_9
		Visibility (screen)	Participants' evaluation of screen visibility in their lecture theatre	X_{10}
	Facility environment	Maintenance	Participants' evaluation of facility maintenance in their lecture theatre	X_{11}
		Accessibility	Participants' evaluation of facility accessibility in their lecture theatre	X_{12}
		Control flexibility	Participants' evaluation of facility control flexibility in their lecture theatre	X_{13}
		Facility standard	Participants' evaluation of facility standard satisfaction in their lecture theatre	X_{14}
		Lecture theatre design	Participants' evaluation of the overall indoor facility environment	X_{15}

Source: Created by the authors

Table 4. KMO and Bartlett's Test of all variables in the questionnaire

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.743
Bartlett's Test of Sphericity	Approx. Chi-Square	4582.665
	df	153
	Sig.	.000

Note: df-degrees of freedom; Sig.-Significance level
Source: Created by the authors

Table 5. Factor loadings and the reliability measures

Items	Rotated factor loadings					
	Facility environment	Thermal environment	Lighting environment	Acoustic environment	Air quality (concentration)	Total
Lecture theatre design X_{15}	0.727					
Control flexibility X_{13}	0.695					
Facility standard X_{14}	0.683					
Accessibility X_{12}	0.654					
Maintenance X_{11}	0.635					
Visibility (screen) X_{10}	0.536					
Thermal comfort scale X_1		0.841				
Thermal comfort for learning X_2		0.841				
Air movment (local) X_3		0.699				
Air quality (local) X_4		0.657				
Lighting quality (local) X_8			0.921			
Lighting quality (general) X_9			0.915			
Acoustic (background) X_6				0.785		
Acoustic (lecturer) X_7				0.718		
Air quality (concentration) X_5					0.913	
Eigenvalue	3.268	2.175	1.526	1.133	1.016	
% of explained variance	18.696	14.916	11.493	8.463	7.226	60.794

Source: Created by the authors

3.3 Basic information of participants and physical facility measurement

Table 6 displays the number of participants, involving 361 males and 308 females in total, with corresponding proportions (54% for males and 46% for females). A clothing ensemble checklist was designed to record participants' clothes. In the winter, the common dress of students inside buildings consisted of a suit of long underwear, one to three long-sleeve shirts or sweaters, one to three pairs of trousers, a jacket, and a pair of shoes. Clothing insulation was estimated based on ASHRAE Standard 55 for typical clothing ensembles in this study (ASHRAE, 2017). In addition, the activity level of the students during the survey was sitting, and according to ASHRAE Standard 55 (ASHRAE, 2017), when sitting on a chair, insulation should be added. Therefore, 0.1 clo should be added since the seat material is consistent with the standard office chair in the actual investigation. Additionally, Table 6 also shows the length, breadth, height, and volume of different lecture theatres, as well as the physical measurements of chairs in different lecture theatres.

3.4 Descriptive results

Figure 5 depicts the descriptive data distribution for 16 field study variables, including thermal environment (A, B), indoor air quality (C, D and E), acoustic environment (F, G), light environment (H, I and J), facility environment (K, L, M, N, and O) and concentration level (P). Different variables are presented in the form of histograms. Taking Figure 5 (A) as an example, Figure 5 (A) shows the overall participants' votes and corresponding effective percentage for thermal comfort in all lecture rooms. The option 'neutral' had the highest frequency among all options with 281, and the corresponding percentage was 42.0%. In addition, the percentage of all students who voted their thermal sensation as comfortable ($-1 < TSV < 1$) is 77% in all lecture theatres. Compared with the comfortable range of thermal sensation, only 14 and 33 students voted 'cold' and 'hot', respectively, which accounts for 2.1% and 4.9% among all participants. For overall votes, more people voted for a warm environment than those who voted for a cold environment. This finding was consistent with a previous study by Jiao *et al.* (2020) on elderly people.

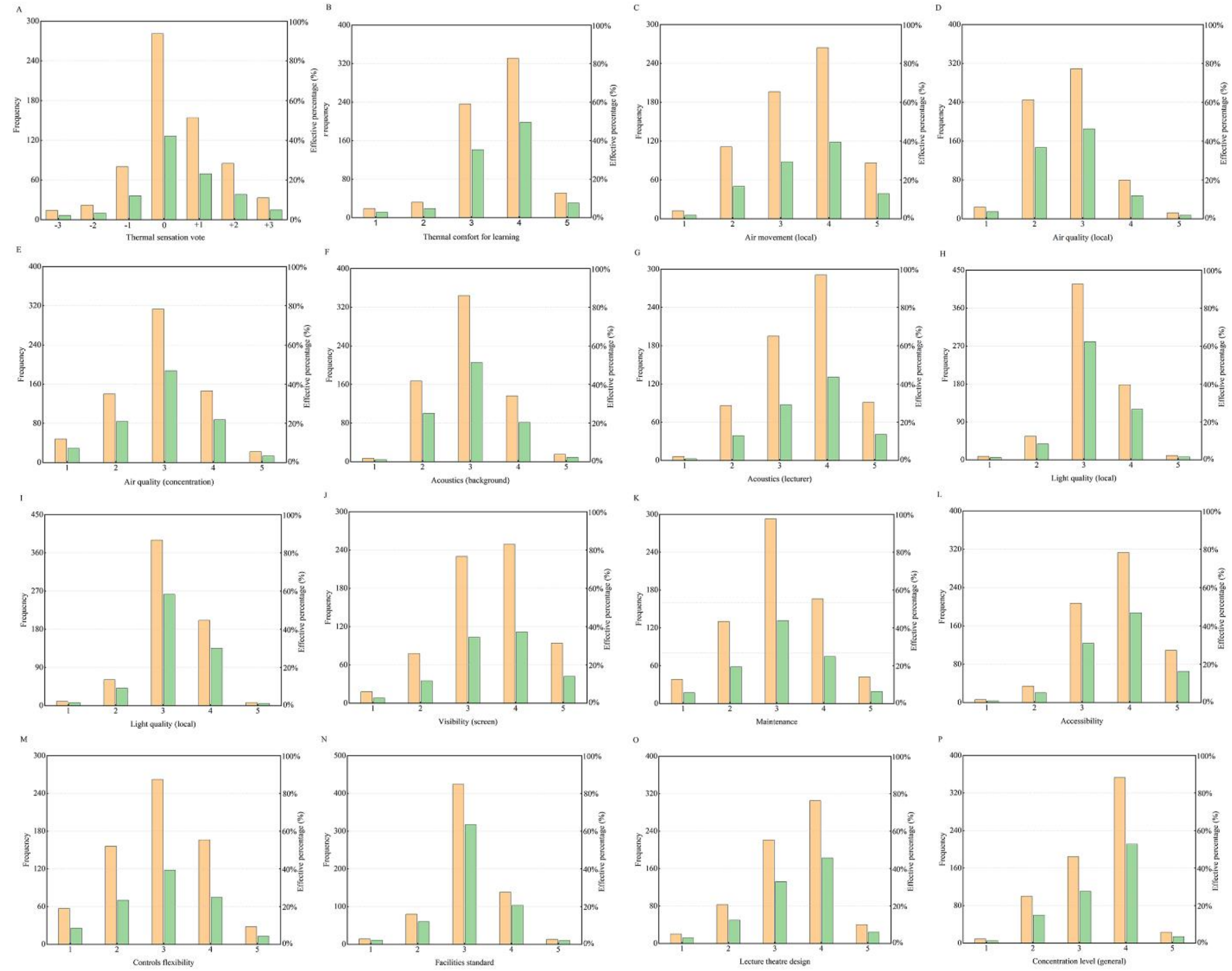
Table 6. Facilities information and demographic information of participants in different lecture theatres

Lecture theatre code	Lecture theatre name	Floor area (m^2)	Space height (m)	Volume (m^3)	Seat width (mm)	Seat depth (mm)	Seat height (mm)	Gender	No.	%
LT1	Anatomy G04 Gavin de Beer LT	84	4.5	378	600	700	800	Male	9	
								Female	2	
LT2	Anatomy G29 J Z Young LT	172	6.2	1066.4	490	400	410	Male	11	
								Female	7	
LT3	Archaeology G6 LT	109	3.3	359.7	470	420	390	Male	8	
								Female	5	
LT4	Bedford Way G03	117	3	351	510	390	410	Male	11	
								Female	9	
LT5	Bedford Way LG04	111	3.2	355.2	470	390	390	Male	6	
								Female	4	
LT6	Chadwick B05 LT	86	3.2	275.2	500	450	450	Male	8	
								Female	10	
LT7	Chandler 118	73	3.1	226.3	470	380	420	Male	4	
								Female	15	
LT8	Chandler G10	177	4.2	743.4	430	390	420	Male	7	
								Female	8	
LT9	Christopher Ingold G21 Ramsay LT	85	3.3	280.5	470	430	390	Male	18	
								Female	12	
LT10	Christopher Ingold XLG1 Chemistry LT	91	3.6	327.6	450	400	400	Male	17	
								Female	23	
LT11	Cruciform B304-LT1	182	6.1	1110.2	480	400	410	Male	37	
								Female	17	
LT12	Cruciform B404-LT2	144	5.5	792	500	400	430	Male	10	
								Female	18	
LT13	Darwin B40 LT	127	4.8	609.6	540	410	430	Male	23	
								Female	15	
LT14	Drayton B03 Ricardo LT	96	3.2	307.2	540	540	420	Male	12	
								Female	4	
LT15	Drayton B20 Jevons LT	192	6	1152	520	460	420	Male	9	
								Female	2	
LT16	Gordon Square (24) 105	58	3.5	203	470	390	450	Male	11	
								Female	9	
LT17	Gordon Street (25) D103	61	3.6	219.6	490	400	400	Male	8	
								Female	5	
LT18	Gordon Street (25) E28 Harrie Massey LT	81	3.2	259.2	410	460	390	Male	7	
								Female	6	
LT19	Gordon Street (25) Maths 500	52	3	156	550	400	400	Male	6	
								Female	5	

(continued)

Lecture theatre code	Lecture theatre name	Floor area (m^2)	Space height (m)	Volume (m^3)	Seat width (mm)	Seat depth (mm)	Seat height (mm)	Gender	No.	%
LT20	Gordon Street (25) Maths 505	62	3.8	235.6	550	430	400	Male	9	
								Female	6	
LT21	Malet Place Eng 1.02	110	6	660	390	380	410	Male	11	
								Female	1	
LT22	Malet Place Eng 1.03	68	3.6	244.8	390	380	470	Male	5	
								Female	3	
LT23	Medawar G01 Lankester LT	125	5.8	725	500	420	400	Male	5	
								Female	16	
LT24	Medawar G02 Watson LT	70	3.4	238	450	450	370	Male	6	
								Female	5	
LT25	Medical Sciences 131 A V Hill LT	106	4.5	477	480	450	450	Male	16	
								Female	13	
LT26	Medical Sciences G46 H O Schild Pharmacology LT	84	3.8	319.2	430	450	430	Male	4	
								Female	8	
LT27	Pearson (Northeast Entrance) G22 LT	158	5.8	916.4	490	420	400	Male	2	
								Female	6	
LT28	Physics A1/3	52	3.2	166.4	450	400	450	Male	12	
								Female	19	
LT29	Roberts 106	103	5.6	576.8	500	380	450	Male	6	
								Female	5	
LT30	Roberts 309	54	3.2	172.8	450	450	550	Male	10	
								Female	0	
LT31	Roberts 421	110	5.4	594	520	420	850	Male	4	
								Female	8	
LT32	Roberts 508	47	3.2	150.4	410	290	420	Male	16	
								Female	9	
LT33	Roberts G06 Sir Ambrose Fleming LT	60	3.6	216	450	400	450	Male	16	
								Female	18	
LT34	Roberts G08 Sir David Davies LT	124	5.8	719.2	500	400	440	Male	7	
								Female	4	
LT35	South Wing 9 Garwood LT	76	3.6	273.6	480	420	390	Male	7	
								Female	0	
LT36	Torrington (1-19) 115 Galton LT	91	4.8	436.8	500	450	410	Male	3	
								Female	11	
In total								Male	361	54
								Female	308	46

Source: Created by the authors



Note: -3, -2, -1, 0, +1, +2, +3 represent cold, cool, slightly cool, neutral, slightly warm, warm, hot respectively in A

1, 2, 3, 4, 5 represent very dissatisfied, dissatisfied, neither dissatisfied nor satisfied, satisfied, very satisfied respectively from B to P

Source: Created by the authors

Figure 5. Descriptive data distribution in different variables in the field study

Table 7. Multiple regression model parameters

Variable	Unstandardized Coefficients		Standardized Coefficients	t-Statistic	Sig.	Collinearity Statistics	
	B	Std.Error	Beta			Tolerance	VIF
C	1.725	0.327		5.278	0.000		
X_1	-0.095	0.027	-0.142	-3.455	0.001	0.568	1.760
X_2	-0.059	0.051	-0.048	-1.161	0.246	0.573	1.745
X_3	0.03	0.03	0.036	1.012	0.312	0.767	1.304
X_4	0.122	0.038	0.118	3.226	0.001	0.712	1.404
X_5	-0.142	0.04	-0.111	-3.516	0.196	0.964	1.037
X_6	-0.076	0.035	-0.069	-2.156	0.031	0.926	1.079
X_7	0.082	0.031	0.089	2.629	0.009	0.831	1.204
X_8	0.043	0.057	0.035	0.744	0.457	0.446	2.242
X_9	0.018	0.059	0.014	0.304	0.761	0.448	2.232
X_{10}	0.033	0.031	0.038	1.074	0.283	0.763	1.310
X_{11}	0.06	0.036	0.060	1.681	0.093	0.761	1.314
X_{12}	0.085	0.03	0.102	2.816	0.005	0.739	1.354
X_{13}	-0.065	0.045	-0.055	-1.444	0.149	0.660	1.515
X_{14}	0.085	0.033	0.097	2.574	0.010	0.670	1.492
X_{15}	0.351	0.037	0.374	9.499	0.000	0.620	1.612

Note: Dependent Variable: Concentration level

Source: Created by the authors

Table 8. Analysis of Variance, ANOVA

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	179.042	15	11.936	28.309	.000[b]
Residual	260.148	617	0.422		
Total	439.189	632			

Note: df-Degree of freedom; F-F test Value

a. Dependent Variable: Concentration levels

b. Predictors: X_1: thermal comfort vote; X_2: thermal comfort for learning; X_3: air movement (local) vote; X_4: air quality (local) vote; X_5: air quality (concentration) vote; X_6: acoustics (background) vote; X_7: acoustics (lecturer) vote; X_8: lighting quality (local) vote; X_9: lighting quality (general) vote; X_{10}: visibility (screen) vote; X_{11}: maintenance vote; X_{12}: accessibility vote; X_{13}: control flexibility vote; X_{14}: facility standard vote; X_{15}: lecture theatre design vote

Source: Created by the authors

3.5 Stepwise multiple regression result

A multiple regression linear model is initially developed, employing the concentration levels of students as the dependent variable and 15 quantitative indicators as the independent variables. By combining many independent variables, the multiple linear regression method aims to effectively predict students' concentration levels and develop a regression model (Lin, 2007). The corresponding value of each variable can be found in Table 7. According to the results, students' concentration levels show negatively correlation with the thermal comfort scale (X_1), thermal comfort for learning (X_2), air quality (concentration) (X_5), acoustics (background) (X_6), and control flexibility (X_{13}). However, air movement (local) (X_3), air quality (local) (X_4), acoustics (lecturer) (X_7), lighting quality (local) (X_8), lighting quality (general) (X_9), visibility (screen) (X_{10}), maintenance (X_{11}), accessibility (X_{12}), facility standard (X_{14}) and lecture theatre design (X_{15}) are positively correlated. The regression significance test is frequently regarded as an overall test of the model's applicability, and variance analysis is employed for evaluation in Table 8. The model passed the test ($p < 0.05$), indicating the model has predictive values.

The residual is the difference between the observed and expected values. The residual in regression analysis is the difference between the observed value and the value predicted by the regression model. Residual analysis involves determining if the residuals are independent of one another, whether the residuals have a normal distribution, and whether the residuals' variance is uniform over the residual diagram. The independence is judged by the Durbin-Watson test. When the statistic is between 0 and 4, it means that the residuals are independent of each other. Autocorrelation may be assumed to be absent from the residual series if the Durbin-Watson statistic is close to 2 (Cohen et al., 2013; Chen, 2016). The value of Durbin-Waston is 1.994 in this model (Table 9), indicating the residuals are independent of each other.

Additionally, the correlation coefficients of variables X_1, X_4, X_6, X_7, X_{12}, X_{14}, X_{15} are smaller than 0.05, suggesting the thermal environment, acoustic environment and facility environment have an influence on the students' concentration levels. However, the lighting environment does not pass the significance level test in the multiple regression model. After filtering independent variables based on the significance level test ($P<0.05$), X_2, X_3, X_5, X_8, X_9, X_{10}, X_{11}, X_{13} were excluded from the model, indicating that these variables have no linear effect on students' concentration level. Therefore, the model is listed as follows:

$$Y_i = 1.725 - 0.095X_1 + 0.122X_4 - 0.076X_6 + 0.082X_7 + 0.085X_{12} + 0.085X_{14} + 0.351X_{15} \quad (2)$$

where Y_i is the dependent variable (concentration levels of students) X_i represents dependent variables (X_1 is the thermal comfort scale, X_4 is the air quality of students' local seats, X_6 is the acoustic from background, X_7 is the acoustic from lecturer, X_{12} is the accessibility, X_{14} is the facility standard, X_{15} is the lecture theatre design).

Table 9. Coefficients of the multiple linear regression model

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics					Durbin-Watson
					R Square Change	F Change	df1	df2	sig. F Change	
Regression residual model	.638a	0.408	0.393	0.649	0.408	28.309	15	617	0	1.994b

Note: a. Dependent Variable: Concentration levels

b. Predictors: X_1: thermal comfort vote; X_2: thermal comfort for learning; X_3: air movement (local) vote; X_4: air quality (local) vote; X_5: air quality (concentration) vote; X_6: acoustics (background) vote; X_7: acoustics (lecturer) vote; X_8: lighting quality (local) vote; X_9: lighting quality (general) vote; X_{10}: visibility (screen) vote; X_{11}: maintenance vote; X_{12}: accessibility vote; X_{13}: control flexibility vote; X_{14}: facility standard vote; X_{15}: lecture theatre design vote

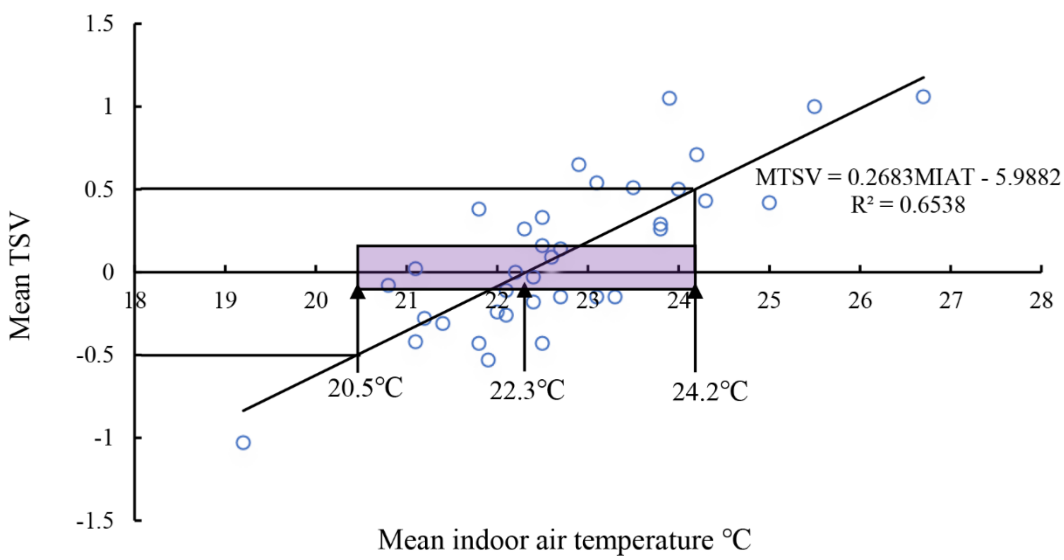
Source: Created by the authors

In this equation, it can be seen that the student's concentration level is positively correlated with factors including X_4 air quality (local), X_7 acoustic (lecturer), X_{12} accessibility, X_{14} facility standard, X_{15} lecture theatre design, and negatively correlated with X_1 thermal comfort scale, X_6 acoustic (background).

3.6 Thermal environment evaluation of the students

3.6.1 The relationship between mean indoor air temperature and mean thermal sensation vote

Figure 6 shows the BIN treatments as scatterplots for the relationship between the mean thermal sensation vote (MTSV) and the mean indoor air temperature (MIAT) of 36 lecture theatres. MIAT was divided into several effective intervals with a 2 ℃ increment. According to Figure 6, MIAT is positively correlated with MTSV, and as indoor air temperatures increase, TSV gradually increases. The slope of the fitting line represents the respondents' thermal sensitivity to variations in MIAT. A rate of 0.268 indicates that the average thermal sensation will increase with one grade for every 5.9 °C increase. Therefore, a 5.9°C MIAT increase could result in a 0.268 MTSV increase. Additionally, if the MTSV equals 0, the thermal neutral temperature can be obtained in Figure 6 is 22.3°C. Students who voted between -0.5 and +0.5 indicate satisfaction with the thermal environment; therefore, the MIAT range in which students are satisfied with the indoor thermal environment is from 20.5°C to 24.2°C in this study. According to formula (2), indoor air temperature exhibits a negative correlation with the concentration level of university students. This implies that when the temperature increases, the concentration level of university students tends to wane. This study finds the neutral temperature of university students is 22.3°C and the comfortable temperature range is from 20.5°C to 24.2°C. Therefore, within the temperature range of 22.3°C to 24.2°C, it indicates that there is a wane in the concentration levels of university students as temperatures increase. However, within the temperature range of 20.5°C to 22.3°C, students' concentration levels could improve when the temperature decreased.



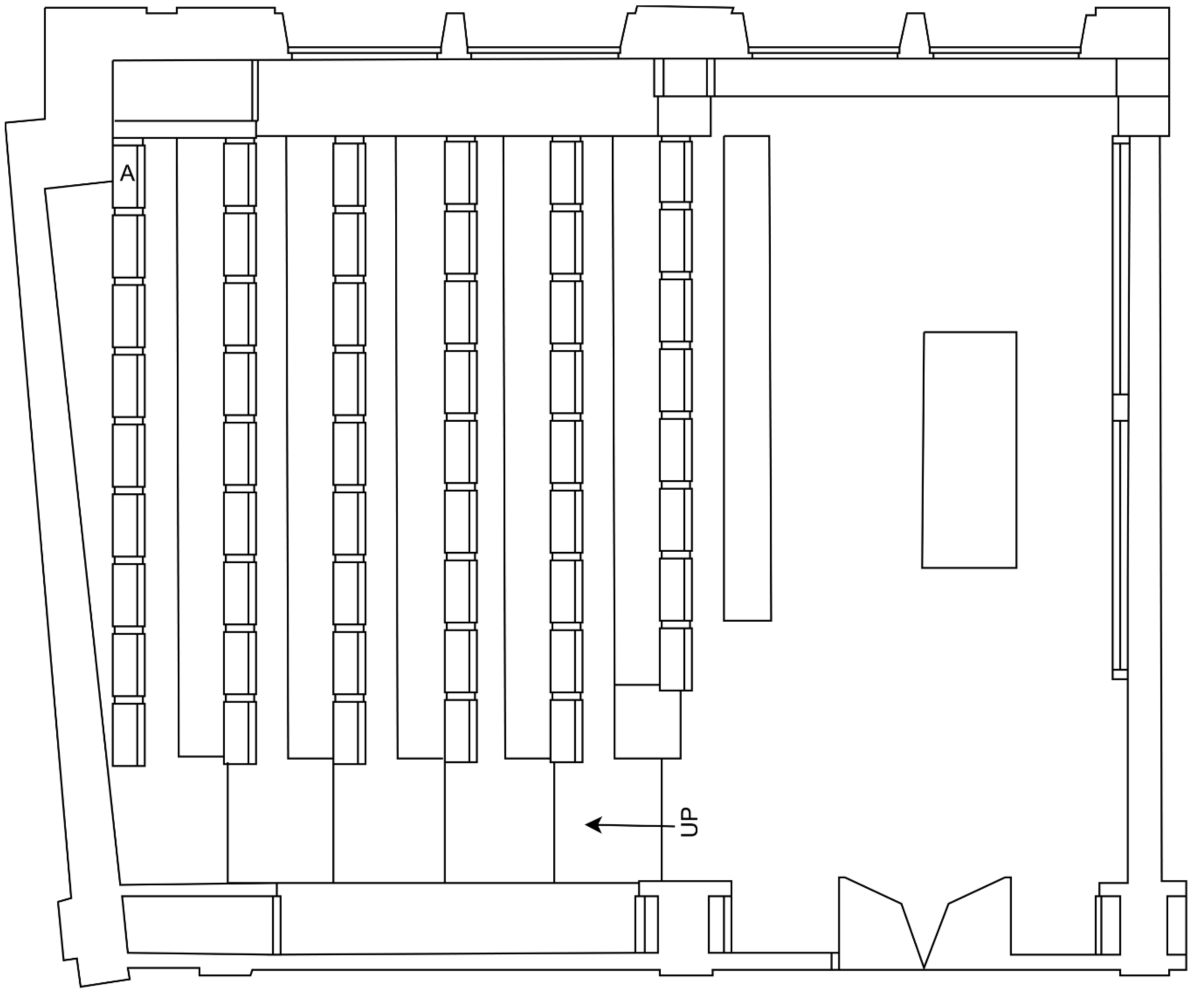
Source: Created by the authors

Figure 6. Relationship between mean indoor air temperature and mean TSV

4. Discussion

4.1 Facility environment of students

This research evaluates the students' evaluation of the facility environment of university lecture theatres based on five factors: maintenance, accessibility, control flexibility, facility standard, and lecture theatre design. The three factors that passed the significance level test are the evaluation of lecture theatre design, accessibility, and facility standard, and their corresponding coefficients are 0.351, 0.085, and 0.085, respectively. According to the formula (2), lecture theatre design is the most significant factor for the student's concentration level in this study, with the largest weight (0.351), and the coefficients X_{12} (evaluation of accessibility) and X_{14} (evaluation of facility standard) of the assessment of the facilities are also positive, showing that these variables have positive associations with students' concentration level at UCL in London. This is in line with the research by Brooks (2011), who confirmed physical space alone could improve student learning beyond the students' ability as judged by standardised test results, even when adjusting for practically all other variables. In this study, it is very interesting that the evaluation coefficient of accessibility and the evaluation coefficient of facility standards are consistent, but the weight of the impact is not great. This is mostly due to the fact that throughout the investigation process, a few lecture theatre seats were close to the wall. Those who find it difficult to access or exit their own seats (student A in Figure 7) also believe that the facility standard does not meet the design requirements. This is mostly due to the rising number of university students exceeding the development rate of university facilities at UCL. Additionally, the older building fabric may impose significant restrictions on interior layouts, requiring special consideration to guarantee structures can operate efficiently and reliably without, for example, compromising security. According to a study conducted by Ahrentzen and Evans (1984), lecturers' and students' perceptions of crowding improved when classroom ceilings were higher, and ceiling height was also substantially correlated with students' overall satisfaction with the classroom. However, Earthman (2004) claimed that one issue with older schools was that their high ceilings "may offset the advantage of increased lighting", while taller ceilings may further exacerbate acoustic issues owing to reverberation. In this survey, student satisfaction with the facility standard achieved 74.9%, indicating that they are satisfied with the entire facility standard, including the lecture theatre height. 15.4% of the dissatisfaction with the lecture design was attributable to the tiny table and tight seating. Some students, however, ascribed their general dissatisfaction to the loss of signal in the classroom and the absence of plugs to charge their laptops. Therefore, future interior design should focus more on providing sufficient table and chair space to improve student satisfaction and concentration.



Source: Created by the authors

Figure 7. One of the sample lecture theatre plans

4.2 Thermal environment of students

According to Figure 6, the neutral temperature in this study was 22.3 ℃. Compared with other investigations, Nikolopoulou and Lykoudis (2006) conducted a 10000-questionnaire field study in 14 different countries and found the same result, they the indicated neutral temperature of people in Cambridge (the same climate zone as London) in the United Kingdom was around 23 ℃. The result is also coherent with the study by De Dear and Brager (1998), which identified the most common and widely adaptive model of thermal comfort. They found that the neutral mean adaptive model had a comfortable temperature of 22 to 23 ℃ when the mean outdoor temperature ranged from 4 to 10 ℃. This study was conducted during the winter in London, with the mean outdoor temperature ranging from 4.8 ℃ to 7.6 ℃ from December to February, thus, this research was adapted to De Dear and Brager's model. However, in Brisbane, the neutral temperature was recorded at 23.8 ℃ (De Dear, 1985). The neutral zone temperature was found to be 24.5 ℃ in the Townsville research in winter (De Dear, 1994). Alghamdi *et al*. (2023) found the neutral temperature of New South Wales university students was 27.5 ℃. The semantics of sensation scales may vary between our research and others due to climate bias. Those who live in warmer climates might prefer to be described as "slightly cool", while those who live in cooler regions prefer the "slightly warm" thermal sensation. In addition, a 5.9℃ MIAT increase could result in a 0.268 MTSV increase; this is consistent with the study by Jiao *et al.* (2017). This is because this study was conducted in winter, and clothing insulation in winter has a greater impact on the occupant's thermal sensation than that in summer.

Regarding the thermal comfort of students in this study of all lecture theatres, they prefer a cooler thermal environment, and the corresponding coefficient is -0.095 based on the results in Table 7. The result is consistent with a previous study by Lan *et al*. (2011), they found that the performance can be reached maximum when the indoor temperature is slightly below neutral. Jensen *et al*. (2009) also confirmed that when the thermal sensation vote of the employee was -1, the optimum performance was obtained. Meanwhile, a field experiment study conducted by Cheng *et al*. (2008) demonstrated students prefer a cooler thermal condition that is 0.6 ℃ lower than neutral temperature in Taiwan. The thermal history and adaptation of a person are one of the key factors in their thermal comfort in an environment. The thermal perception of a space's occupants is influenced by the difference between their present and previous environmental experiences (Ji *et al*., 2017). In the winter months in London, the difference between interior and outdoor temperatures may reach 15 degrees or even more. University students will typically be in a transitory condition for between 20 and 30 minutes each time they move in and out of the classroom after every class. After that, they will adopt adaptive behaviours to restore their thermal comfort. Therefore, the temperature difference between the exterior and transition space, as well as the temperature difference between the transition space and the interior, may have significant impacts on the comfort level of the subjects (Jiao *et al*., 2023).

4.3 Indoor air quality and the acoustic environment of students

The interior air quality, which is a measurement of the air inside a building, has a significant impact on educational productivity (Tagliabue *et al*., 2021). Jia *et al.* (2021) found the performance of students tends to decrease significantly when the indoor air quality worsens through a literature review. Air quality (local) is the only factor used to evaluate indoor air quality in this study. The air quality where students were seated was positively correlated with the students' concentration level, with a corresponding coefficient of 0.122, which indicates that the higher the air quality, the greater the students' concentration. This is consistent with a study by Twardella *et al*. (2012), through experimental studies with 20 classrooms in Germany, they found reduced attention performance of students has a close relationship with deteriorated air quality. Specifically, in the two control experiments, the students who provided fresh air (mean CO2 of 593–783 PPM) improved the accuracy rate of addition tests by 9% compared with the students who recirculated the classroom air (mean CO2 of 1638–4093 PPM). In this study, several students struggled to concentrate in class because of the stuffy air, which often made them feel sleepy. In order to improve indoor air quality, the key is to increase ventilation. It is suggested that architects renovate inadequately ventilated classrooms by evaluating building orientation, indoor ventilation, employing passive design strategies, and meticulously designing window positions and indoor space layout. With a passive design strategy, natural ventilation may be attained with no additional equipment.

Sound has an influence on spatial perception. In architectural space, noise is annoying, distracting, and may directly disguise cognitive processes; it also reveals a propensity for noise to be disruptive, which in turn reduces productivity. Concerns about long-term exposure to noise from aircraft and traffic prompted studies of the impact of learning in noisy environments. In this study, background noise has a negative connection with students' concentration level, while the effect weight is not significant (0.076), which is in line with a study by Braat-Eggen et al. (2021), they found that an increase in background noise had a negative impact on student attention. However, this study reveals a positive correlation (0.082) between the lecturer's voice and the student's concentration level; in the questionnaire, many students were unable to hear the speaker properly due to their distant seats. In addition, some students are unable to focus owing to the microphone's echo and the air conditioner's noise. These factors could explain the effect of sound on students' concentration levels. However, three factors regarding the lighting environment did not pass the significance level test in this study. This is due to the fact that throughout the actual research process, the lighting environment in the majority of classes is relatively the same, and students in various classrooms are exposed to almost identical lighting conditions. Therefore, the acoustic environment will have no influence on the concentration level of students in this study.

5. Limitation

Several limitations of our work should be recognised. First, without taking into account the conditions in the spring, summer, and fall, this study was conducted exclusively in the winter. Future studies should be conducted continuously throughout the year to collect data for a full calendar years' worth of investigation. Second, this study included many factors in the questionnaire, but the objective environmental parameters measured during the actual survey were only temperature. Other environmental factors, including air quality, the sound level, lighting level, and other physical parameters, should be incorporated into the climate chamber to conduct the experiment. For the purpose of establishing a comprehensive physical indoor environment assessment and comparing it to existing studies.

6. Conclusion

A series of field study tests were conducted to examine the influence of IEQ of the university on students' concentration levels. In London, 669 students' subjective questionnaires regarding the thermal environment, the acoustic environment, the illumination environment, and the facility environment in 36 lecture theatres were collected. The goal of this study was to examine the influence of IEQ of the university on students' concentration levels. The main findings of our research are as follows:

Lecture theatre design was the most significant factor influencing students' concentration levels. And facility environment was more important than thermal environment, indoor air quality, and acoustic environment in influencing students' concentration levels in this winter investigation at UCL, UK.

Accessibility and facility standards have the same level of influence on students' concentration levels, and their corresponding coefficients are both 0.085. Larger and more comfortable tables and chairs should be prioritised in the design of new indoor facilities, and certain seats in UCL lecture theatres should be moved away from the walls to improve students' accessibility throughout the lecture theatres, thus improving their concentration levels.

In terms of the thermal environment, the neutral temperature for students in this survey was 22.3°C, the satisfactory range for voting on thermal comfort corresponds to an indoor temperature range of 20.5°C to 24.2°C, and students prefer a colder thermal environment.

The concentration level of students was positively correlated with the air quality where they sat, with a coefficient of 0.122. Regarding the acoustic environment, background noise has a negative correlation with students' concentration level, even though the effect weight is not statistically significant (0.076); however, this study reveals a positive correlation (0.082) between the lecturer's voice and students' concentration level.

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