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Perceived indoor air quality in naturally ventilated primary schools in the UK: Impact of environmental variables and thermal sensation

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Abstract

Indoor air quality (IAQ) in classrooms has a significant impact on children's academic performance, health, and well-being; therefore, understanding children's perception of IAQ is vital. This study investigates how children's perception of IAQ is affected by environmental variables and thermal sensation. In total, 29 naturally ventilated classrooms in eight UK primary schools were selected and 805 children were surveyed during non-heating and heating seasons. Results show that air sensation votes (ASVs) are more correlated to CO_2 levels than to operative temperatures (T_{op}) during non-heating seasons and more correlated to T_{op} than CO_2 levels during heating seasons. The impact of T_{op} on ASVs decreases with an increase in CO_2 levels, and the effect of CO_2 levels on ASVs decreases with increase in T_{op}. The most favorable ASVs are given when children feel "cool" and have "as it is" preference. By keeping $CO_2 < 1000$ ppm and T_{op} within children's thermal comfort band, ASVs are improved by 43%. The study recommends that standards should consider the impact of both temperature and CO_2 levels on perceived IAQ. Perception of IAQ also affects children's overall comfort and tiredness levels; however, this influence is more significant on tiredness level than that on overall comfort level.

KEYWORDS

air sensation votes, children's perception, CO_2 levels, indoor air quality, naturally ventilated, operative temperature

1 | INTRODUCTION

Classrooms are the second most important indoor environment for children after their homes [1] because children spend around 25%-30% of their life in schools.[2-4] Concerns over adverse effects of poor indoor air quality (IAQ) on children's health, productivity, and well-being are growing,[5-8] especially because indoor air can be 10 times as polluted as the outdoor air in real conditions.[9] Poor IAQ leads to some psychological or physiological costs,[10] and influences students' health and performance, especially in younger ages.[11] Building regulatory frameworks for the provision of adequate IAQ is framed around CO_2 levels rather than other pollutants.[12] IAQ is often characterized by CO_2 concentrations,[13-18] in buildings where exhaled air, people, or bio-effluents are the main pollution sources.[19-21] Carbon dioxide (CO_2) as the most important human bio-effluent[22-24] is produced by human respiration[14] in proportion to their metabolic rate.[23]

The introduction signifies the importance of CO_2 levels on children's absenteeism, health, and academic performance by reviewing the results of several studies. Studies have shown that children's exposure to poor IAQ increases school absenteeism[25] and deteriorates respiratory system.[25-27] The study by Shendell et al (2004) shows that when CO_2 concentrations increase by 1000 ppm, around 10%-20% of absenteeism is increased.[13] Seppänen et al (1999) suggest that decreasing CO_2 concentrations below 800 ppm can decrease the risk of sick building syndrome (SBS) symptoms, such as headache, fatigue, or eye/throat irritation.[28] Myhrvold et al (1996) show that CO_2 concentrations greater than 1500 ppm may lead to headache, dizziness, tiredness, difficulties in concentrating, and unpleasant odor in classrooms.[29]

It is shown that adverse health effects and absenteeism caused by poor IAQ can negatively affect children's academic performance.[30,31] Several studies have found a negative correlation between high CO_2 levels and performance on cognitive and concentration tests.[32-34] Coley et. al (2007) show that increase of CO_2 levels from a mean of 690 ppm to a mean of 2909 ppm leads to a 5% decrease in Power of Attention.[32] Berner (1993) shows that average students' test scores increase 5.4 points ($P < .05$) for each improved category of building conditions (ie, "poor" to "fair" to "excellent").[34] Myhrvold et al (1996) by studying 550 subjects aged 15-20 in 20 classrooms in Norwegian schools show that increased CO_2 levels, corresponding to 0-999, 1000-1499, and 1500-4000 ppm, are associated with mean performance indices of −0.8, 0.02, and 0.13, respectively (negative scores representing better scores).[29] Children as the main occupants of primary schools represent a vulnerable group[35-38]; therefore, improving IAQ is significant for them. Abovementioned studies highlight the impact of CO_2 levels on IAQ, health, and productivity; however, children's perception of IAQ with regard to environmental and sensation variables is less investigated, especially in primary schools.

It is important to investigate school children's perception of IAQ due to their physical and physiological differences with adults. Physically, young children are more susceptible to indoor air pollution compared to adults due to higher air intake in proportion to their body weight[39-43] and less developed organs, tissues, and immune system.[42] Physiologically, children have higher respiration and metabolic rates.[44] External factors such as type of work[30,45] and stress level[46] can also impact children's perception of IAQ negatively. Since primary school children's perception of IAQ is less investigated, the study aims to investigate the association between children's perception of IAQ with environmental variables (such as CO_2 levels and operative temperature) and thermal sensations in naturally ventilated classrooms. It also looks at the impact of children's air sensation votes (ASVs) on their overall comfort and tiredness levels.

2 | METHODOLOGY

The five main steps carried out in this methodology are as follows: (1) defining research design; (2) sampling climate, buildings, and occupants; (3) acquiring data on children's perception of the indoor environment and environmental measurements; (4) evaluating classrooms' IAQ against standards; and (5) reviewing statistic methods for analysis.

Practical Implications

- Air sensation votes are correlated with the last 5 minutes of CO_2 measurements.
- Perception of air quality is affected by CO_2 levels and operative temperature.
- When children feel "hot or cold," air sensation votes are the least favourable.
- When "CO_2 < 1000 ppm and T_{op} < 23°C," perception of air quality is improved by 43%.
- Standards should consider the impact of both operative temperature and CO_2 levels on perceived IAQ.
- Better perception of indoor air quality results in higher overall comfort votes.

2.1 | Research design

The design of the study defines transverse sampling in which according to Nicol et al (2012) bias is lowered or avoided; thus, the results are more representative.[47] The problem with longitudinal sampling in this type of study is that many intervening variables may affect studied variables during a lengthy time.[48] There is a danger of sampling bias in longitudinal studies[47] which is due to the small population. Participants might lose interest in participating due to high frequency of surveys[49] in longitudinal studies. Hence, data acquisition and observations were carried out in 29 different classrooms on 29 distinct days throughout one year. To increase the validity of the study and reduce bias, the number of studied classrooms is similar during both seasons, 15 classrooms during non-heating and 14 classrooms during heating seasons.

2.2 | Sample selection

Samples were selected with specific attention to climate, buildings, and observed occupants.

2.2.1 | Location

Schools were selected in the *mild* climate of UK for two main reasons: (1) Mild or temperate climates where the outside temperature is lower than indoor temperature can provide opportunities for buildings' natural ventilation, as supported in several other studies.[50-52] Mumovic, et al. (2018) suggest that outdoor temperature in the UK is lower than the indoor temperature for most of the year during both day and night[51]; therefore, window opening can ventilate and cool

TABLE 1 Classroom's architectural features and configurations

Mode/Date		General		Classroom			Window Design						
		No.	Floor	Orn[1]	Area	Vo[2]	WA[3]	NW[4]	W Type	Ventilation	MHW[5]	W Operation	Exterior Door
Non-heating	July and Sep 2017	1.1	First	NE	60	192	8	8	Top-hung outward openings at 2 levels	Single-sided windows at 2 level + louvre opening	1	Manually	No
		1.2	First	SW	60		8	8			1	Manually	No
		1.3	First	SW	60		8	8			1	Manually	No
		1.4	First	SW	60		8	8			1	Manually	No
		2.6	First	NW	60	192	8	8	Top-hung outward openings at 2 levels	Single-sided windows at 2 level + louvre openings	1	Manually	No
		2.7	First	SE	60		8	8			1	Manually	No
		2.8	First	SE	60		8	8			1	Manually	No
		2.9	First	NW	60		8	8			1	Manually	No
Heating	Oct & Nov 2017	3.10	Ground	S &W	65	227	2	5	Top-hung outward	Single-sided	1.7	Manually	Yes
		3.11	Ground	S &W	70	245	2.2	6		Double-sided	1.6	Manually	No
		3.12	First	NW	60	192	2.5	5		Single-sided	2.6	With handle	No
		4.13	Ground	W	50	130	0.5	2	Top-hung outward	Single-sided	1.8	Manually	Yes
		4.14	Ground	W	60	156	0.5	2			1.8	Manually	Yes
		4.15	Ground	No W	50	175	0	0	-	No opening	-	No window	No
	Jan and Feb 2018	5.16	First	SW, SE	55	137	5.7	8	Top-hung openings at 2 levels	Single-sided at two levels	0.5	Manually	No
		5.18	First	SW & NW	55		5.7	8			0.5	Manually	No
		5.20	Ground	SW & NW	55		5.7	8			0.5	Manually	Yes
		6.21	First	SE	60	168	1.8	4	Top-hung outward opening	Single-sided windows + Louvre openings	2.3	Remote-control	No
		6.22	First	SE	60		1.8	4			2.3		No
		6.23	First	SE	60		1.8	4			2.3		No
		6.24	First	SE	60		1.8	4			2.3		No
		6.25	First	SE	60		1.8	4			2.3		No

(Continues)

TABLE 1 (Continued)

Mode/Date		General		Classroom			Window Design						
		No.	Floor	Orn[1]	Area	Vo[2]	WA[3]	NW[4]	W Type	Ventilation	MHW[5]	W Operation	Exterior Door
Non-heating	April and May 2018	7.26	Ground	SE & SW	70	252	3.9	6	Top-hung outward opening	Double-sided	2.7	With handle	No
		7.27	Ground	SE & SW	55	137	3.3	3		Single-sided	1.65	Manually	Yes
		7.28	First	NE & NW	55	137	5.4	6		Double-sided	1.6	Manually	No
		8.29	Ground	NE	60	150	2.2	4	Top-hung outward opening	Single-sided	1.4	Manually	Yes
		8.30	Ground	NE	60	150	2.2	4			1.4	Manually	Yes
		8.31	Ground	NW	55	137	2.2	4			1.4	Manually	Yes
		8.32	Ground	NW	55	137	2.2	4			1.4	Manually	Yes

[1]Orientation.
[2]Volume(m^3).
[3]Window area (m^2).
[4]Number of windows.
[5]Minimum height of window sill (m).

the building. (2) Mild climates can reduce the biased impact of one extreme climate to let investigate window operation in NV buildings during both non-heating and heating seasons. This study was carried out in Coventry, West Midland from July 2017 until the end of May 2018. Both seasons were studied because variations in temperature and relative humidity would influence students' perception of the indoor environment.[53,54] Measurements during schools' occupied time show that outdoor temperatures varied between 11.5-24.9°C with a mean of 18.1°C during non-heating seasons and changed between 3.5-14.2°C with a mean of 7.8°C during heating seasons. Outdoor variables were taken from Met office local weather stations[55] that were maximum 3 miles away from each study site.

2.2.2 | Buildings

In this study, 29 NV classrooms were selected in eight primary schools that comply with the following five criteria. (1) Selected schools are naturally ventilated since the main source of ventilation in most schools in the UK is windows. Furthermore, variations in temperature, relative humidity, and indoor pollutants from mechanical ventilation and air-conditioning systems[53,54] can impact children's perception of IAQ. (2) Schools were selected in quiet areas with a considerable distance to the main road to not restrict window operation due to high background noise level as recommended by Building Bulletin 93: Acoustic Design of Schools to facilitate natural ventilation.[56] The regional Road Noise, LAeq 16h, is less than 55 dB in all selected schools according to England Noise Map Viewer.[57] (3) Schools were also selected in low-polluted areas to not restrict window operation, as recommended by CIBSE TM 21: Minimizing pollution at air intakes.[58] Schools were selected in areas with low Daily Air Quality Index (DAQI) according to Air pollution Forecast provided by the Met Office.[59] (4) Buildings were selected with different architectural features as studies have shown that buildings' design affects IAQ.[24,38,60] Classroom's architectural features are shown in Table 1; classroom area (50-70 m^2), volume (130-252 m^3), window area (0-8 m^2), number of windows (0-8), and the minimum height of windowsill (0.5-2.3 m). 5. Schools were selected among both renovated and existing buildings because buildings have different potentials for maintaining IAQ according to their age and design.[42,60,61] Furthermore, the required IAQ is different for renovated and existing buildings.[62] Among 29 classrooms, 13 classrooms are renovated and 16 classrooms are not.

2.2.3 | Occupants

It is important to select an age-group that has a good understanding of questionnaire structure and indoor environment. Among primary school students, children in their late middle childhood (9-11 YO) rather than their peers in early middle childhood (6-8 YO) were selected as the main respondents of this study because of their more developed literacy skills, cognitive abilities,[63] and attention span.[64]

TABLE 2 Questions on indoor quality taken from the self-reported questionnaire designed by authors[65]

Variables	Questions	Scales and coding				
Indoor Environment Quality	How do you feel now?	Cold (−2) □	Cool (−1) □	OK (0) □	Warm (+1) □	Hot (+2) □
	How is the air in the classroom now?	Very fresh (1)□	Fresh (2)□	OK (3)□	Stuffy (4)□	Very Stuffy (5)□
	I like the air to be ... now.	Fresher (1) □		As it is (2)□		
	Do you feel comfortable now?	I am comfortable (1)□	I am a little comfortable (2)□		I am not comfortable (3)□	
	Do you feel tired now?	I am not tired now (1)□	I am a little tired now (2)□		I am tired now (3)□	

Note: Worst judgment on IAQ = Vote 5 (very stuffy), worst judgment on comfort and tiredness level = Vote 3 (I am not comfortable, and I am tired now). Colors are designed based on children's perception of the votes. For example, red shows hotness and blue shows coldness.

They evaluate facts better,[64] which results in data validity and consistency of findings.[63] The gender ratio of surveyed girls (51%) and boys (49%) is approximately the same that can reduce bias and increase the credibility of results.[65]

2.3 | Data acquisition

2.3.1 | Children's perception of indoor environment

This study acquires data on children's **A**ir **S**ensation **V**otes (ASVs) and **T**hermal **S**ensation **V**otes (TSVs) through a self-reported questionnaire that was validated in an earlier study by authors,[65] Table 2. Children's perception of IAQ was questioned by "How is the air in the classroom now?" with a 5-point rating scale as "Very fresh, Fresh, OK, Stuffy and Very stuffy". This question is followed by another question to find out if they want the air to be "Fresher" or "As it is." Several other studies confirm that CO_2 concentrations determine children's perception of air freshness and stuffiness.[33,66,67] To evaluate how **T**hermal **S**ensation **V**otes (TSVs) affect ASVs, children were surveyed on the thermal environment by "How do you feel now?" with a 5-point rating scale as "Cold, Cool, OK, Warm, Hot." To discover how comfort and tiredness levels are related to ASVs, two other questions, "Do you feel comfortable now?/Do you feel tired now?," were administrated to children by 3-point rating scales, Table 2.

According to Building Bulletin 101 (2018), the internal air quality in schools is determined largely by odor (from people and materials) and CO_2 levels, rather than any other pollutants.[8] Therefore, during the pilot study, another question was designed for evaluating children's perception of IAQ; "Is your classroom smelly now?".[65] However, this question was removed from the questionnaire during the validation process[53] since no correlation was found between CO_2 levels and answers to this question. This is mainly because occupants already in the room will not be aware of odor, as a reaction to odor is immediate and olfactory sense rapidly adjusts to odor.[68] Studies have shown that CO_2 concentrations better account for children's perception of air freshness[66,67] than children's perception of smell.[65]

Children were usually asked to fill out the paper-based questionnaire at the end of morning and afternoon sessions because the end of sessions has the poorest conditions in terms of IAQ due to accumulation of stale air.[21] In total, questionnaires were filled out on 52 different morning and afternoon sessions. Goto et al (2002)[69] suggest that occupants should maintain a stable activity level at least 30 minutes before filling out the questionnaire. Therefore, the authors made sure that children maintained sedentary activities (reading and writing) at least 30 minutes before filling out the questionnaires. Running surveys resulted in observing 805 children and collecting 1390 questionnaires, Table 3.

TABLE 3 The number of schools, classrooms, and children observed

School Number	Date	Number of classrooms	Number of surveyed & observed children	Number of collected questionnaires
School 1	July 17-21, 2017	5	130	210
School 2	September 21-27, 2017	4	110	195
School 3	October 29-31, 2017	3	65	115
School 4	November 21-24, 2017	3	85	115
School 5	Jan 29-Feb 02, 2018	5	145	290
School 6	Feb 12-16, 2018	5	85	140
School 7	April 17-19, 2018	3	80	165
School 8	May 22-25, 2018	4	105	160
Total	July 2017- May 2018	32	805	1390

TABLE 4 CO_2 levels and expected percentage dissatisfied by EN 13779:2007 for each category of IAQ[62]

Categories	IAQ standard	Expected percentage dissatisfied	Range of CO_2 levels	Total CO_2 level based on outdoor CO_2 of 400 ppm
Category I	High	<15	<400	<800
Category II	Medium	15-20	400-600	800-1000
Category III	Moderate	20-30	600-1000	1000-1400
Category IV	Low	>30	>1000	>1400

2.3.2 | Environmental measurements

Environmental variables affecting IEQ and comfort were recorded at 5-minute intervals; however, environmental variables recorded at the time of children's filling out the questionnaire are evaluated in this study. Environmental variables were recorded at 5-minute intervals by multi-functional SWEMA equipment, standalone data loggers, and CO_2 meter (TGE-0011, accuracy: ±50 + 2%). Measurement station was located away from the main airflows (eg, windows), away from heat sources (eg, projectors), and also away from sun patches at a height of 1.1 m as recommended by ISO 7726.[70] Equipment was placed within the vicinity of children's desks without impairing their visual access and seating arrangement. The instruments were set up in the classrooms before children's arrival in the morning so that instruments acclimatize to the classrooms' environment before reading.[47]

2.4 | IAQ standards

The European standard of EN 13779:2007[62] recommends IAQ values and expected percentage dissatisfied in four different building categories, Table 4": (I) high level of expectation for spaces occupied by very sensitive people with special requirements, (II) normal level of expectation for new buildings and renovations, (III) moderate level of expectation for existing buildings, and (IV) low level of expectation only acceptable for a short period.

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standard 62 recommends CO_2 level of 1000 ppm for classrooms,[14] which is similar to that for Category II buildings for new and renovated buildings.

2.5 | Statistical analysis

To decide on the most appropriate statistical tests, parametric and non-parametric tests are defined.

Parametric tests can only be used when data fulfill these three conditions: (1) the level or scale of measurement is of equal interval or ratio scaling, (2) the distribution of the population is normal, and (3) the variances of both variables are equal.[71,72]

To check the normality of the interval-scale data, histograms, Kolmogorov-Smirnov/Shapiro-Wilk's tests and QQ plots are applied.[73] In histograms, the normally distributed data peak in the middle and are symmetrical about the mean (bell-shaped)[73]; however, it does not need to be perfectly normally distributed.[74] For Kolmogorov-Smirnov/Shapiro-Wilk's tests, normality tests are unlikely to detect non-normality for small sample sizes ($n < 20$) and are too sensitive for larger sample sizes ($n > 50$).[73] In QQ plots, the points will be close to the line for normally distributed data.[74] Because Kolmogorov-Smirnov/Shapiro-Wilk's tests are sensitive to outliers, histograms for large samples and QQ plots for small samples can be used.[74] To check homogeneity of variance, Levene's test (part of standard SPSS output) can be used.[74]

In this study, histograms and Levene's tests are used to check the distribution and variance of the dependent variable of air sensation votes (ASVs). Results of this study show that air sensation votes, as dependent in this study, are approximately normal (bell-shaped), as shown in Figure 1; however, Levene's test shows that variances are not equal, [F (4, 1354) = 14.7, P = .000]. The data were analyzed using the Statistical Package for Social Science (SPSS).[75]

Statistical analysis in the following is categorized into four main groups: (1) descriptive, (2) correlational, (3) predictive, and (4) group differences (cause and effect). Table 5 shows a summary of tests done in this study based on the type of dependent and independent variables.

2.5.1 | Descriptive statistics

Descriptive statistics such as (minimum, maximum, mean, and standard deviation) can describe normal distribution of variables.[74] In this study, descriptive statistics are used to describe the dependent variable of ASVs which is normally distributed.

2.5.2 | Correlational

Correlation indicates both the strength and direction of the relationship between a pair of variables.[71,72] It is assumed that higher correlation coefficient values and smaller associated P values imply a stronger correlation.[76] Spearman's correlation is a non-parametric measure used for ordinal/interval and skewed data to show the strength of the relationship.[71-73]

2.5.3 | Predictive

Regression explains how variables are related and it predicts dependent variable (y) given the independent variable (x),[74] ($y = a + bx + e$, $R^2 = n$). The R^2 value shows the proportion of the variation in the dependent variable which is explained by the model.[71,72,74] In this study, correlations and regressions are used to show how ASVs are related to T_{op} and CO_2 levels, Table 5.

2.6 | Group differences

Tests of group differences are used to determine whether the groups are the same or not.[71,77] Chi-square test is used to compare proportions between two or more independent groups,[15,71-73] and Kruskal-Wallis test is used to compare the medians between groups.[71-73] In this study, chi-square and Kruskal-Wallis tests are used to show how frequency and median of ASVs change in different categories of TSVs, IAQ, operative temperature (T_{op}), and tiredness, Table 5.

3 | RESULTS AND DISCUSSION

The study provides an overview of the recorded data on children's perception of the indoor environment and indoor environmental conditions. The first part of the study shows factors affecting ASVs including physical parameters (such as CO_2 levels, operative temperature, and humidity) and thermal sensation. The second part of the study shows factors that are affected by ASVs such as comfort and tiredness levels, Figure 2.

3.1 | Overview of the recorded data

- **Perception of Indoor Environment:**

The frequency of children's ASVs (%) and **A**ir **P**reference **V**otes (APVs) during different seasons is shown in Figure 3. This figure shows that proportion of "OK" votes is the highest (40.3%), followed by "fresh or very fresh" votes (36.2%) and then "stuffy or very stuffy" votes (23.5%). The frequency (%) of comfort and tiredness votes during different seasons is shown in Figure 4.

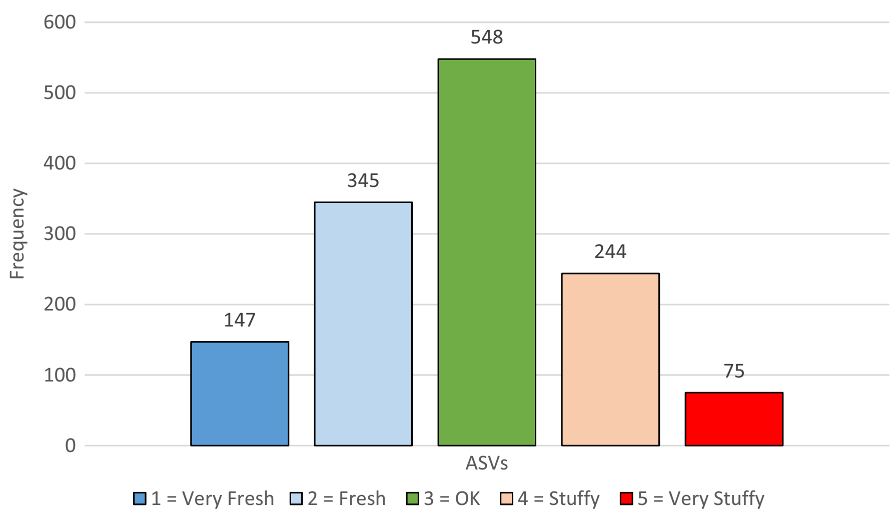


FIGURE 1 Normal distribution of ASVs

TABLE 5 Summary of all tests in this study

Variables			Variables in this Study	
Independent (IV)	Dependent (DV)	Corresponding Test	Dependent	Independent
1 interval IV	Ordinal or interval	Non-parametric Spearman correlation[71-73]	ASVs	CO_2 levels
				T_{op}
1 IV with 2 or more groups	Ordinal or interval	Non-parametric Kruskal-Wallis test[71-73]	ASVs	TSVs
	Categorical	Non-parametric chi-square test[71,72]	ASVs	Different Cat of IAQ
				Different Cat of T_{op}
				Different Cat of Tiredness

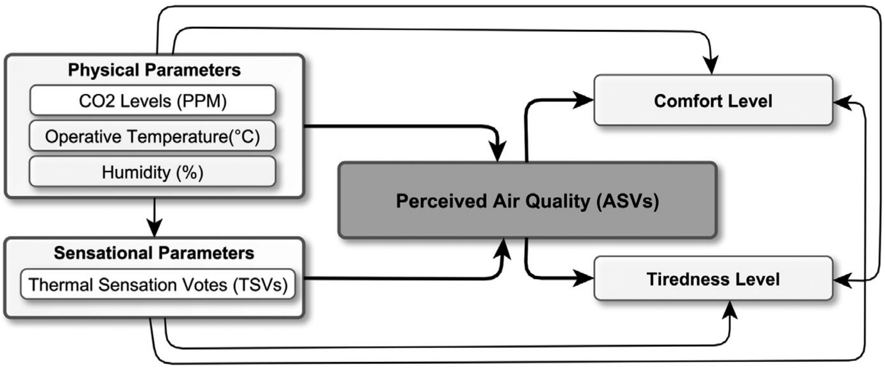


FIGURE 2 Classification of results and findings

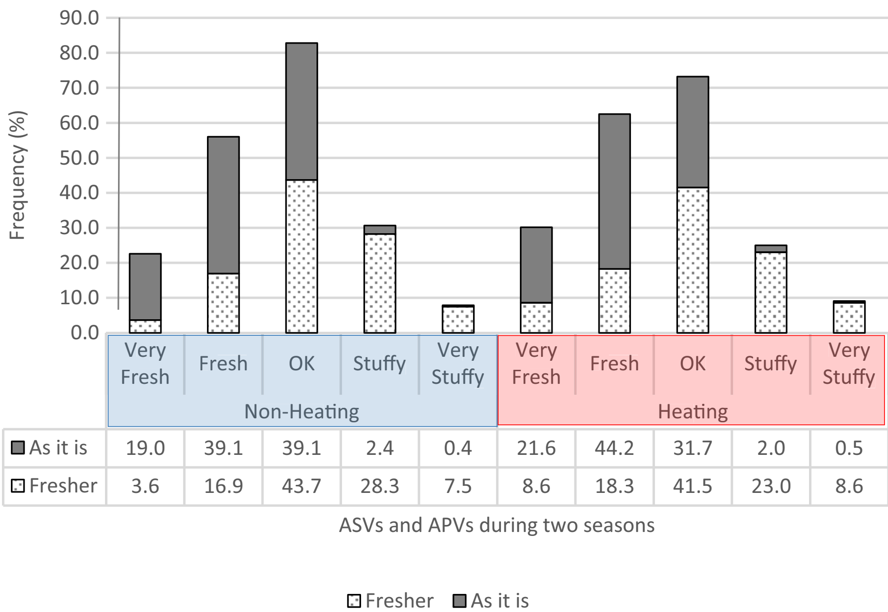


FIGURE 3 Frequency (%) of ASVs and APVs during different seasons

As can be seen in Figure 4, "comfortable" votes are the highest (51.4%), followed by "a little comfortable" (34.7%) and "not comfortable" (13.9%). Similarly, "a little tired" votes are the highest (40.8%), followed by "tired" votes (33.8%) and "not-tired" (25.4%) votes, Figure 4.

- **Indoor Environmental Conditions:**

Descriptive statistics of environmental variables *at the time of filling out questionnaires* are presented in Table 6. Mean CO_2 level is higher during heating seasons (1310 ppm) than that during non-heating seasons (1180 ppm). Maximum air velocity is below 0.1 m/s in this study; therefore, operative temperature (T_{op}) was calculated based on the average of indoor air temperature and radiant temperature.[47,78] Mean operative temperature and humidity during non-heating seasons (24.2°C and 50.9%) are higher than those during heating seasons (22.8°C and 37.3%).

Figure 5 shows frequency (%) of "at-the-time CO_2 levels" in each category of IAQ during non-heating and heating seasons. Measurements of "at-the-time CO_2 levels" are mostly distributed in categories III and IV and CO_2 levels in Cat I are only recorded during non-heating seasons, Figure 5.

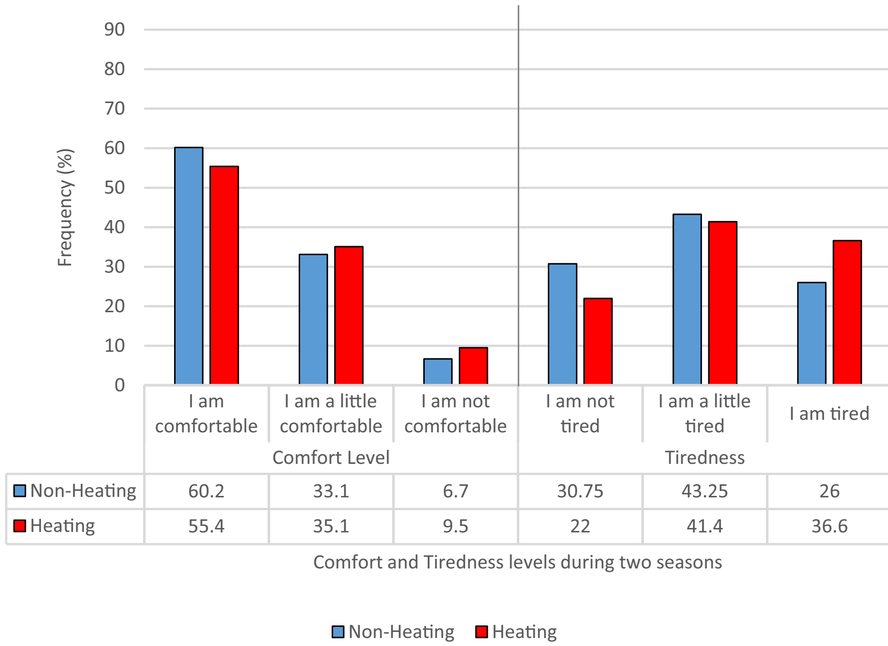


FIGURE 4 Frequency (%) of comfort and tiredness votes during different seasons

TABLE 6 Descriptive statistics of environmental variables at the time of filling out the questionnaire

Season	Parameters	Minimum	Maximum	Mean	SD
Non-heating	CO_2 level (ppm)	662	3277	1180	488
	Air velocity (m/s)	0.00	0.1	0.08	0.05
	Operative temperature (°C)	19.0	28.1	24.2	2.1
	Relative humidity (RH)	38.3	66.6	50.9	7.8
Heating	CO_2 level (ppm)	842	2106	1310	351
	Air velocity (m/s)	0.00	0.09	0.05	0.03
	Operative temperature (°C)	18.9	26.8	22.8	1.7
	Relative humidity (RH)	25.8	53.4	37.3	7.4

Table 7 shows mean operative temperatures and their standard deviations (SD) in each category of IAQ. As can be seen in Table 7, mean operative temperature and SD are higher when CO_2 levels are lower than 800 ppm (Category I) compared to other categories.

3.2 | The impact of CO_2 levels on ASVs

The impact of CO_2 levels on ASVs is investigated by predicting the strength of the relationship (correlations), degree of variations (regressions), and predicted percentage dissatisfied (PPD).

3.2.1 | Strength of relationship (Correlations)

CO_2 levels affect occupants' perceived IAQ[19,28] and determine occupants' perception of air freshness and stuffiness.[66,67] Results of this study, using Spearman correlation coefficient test, show that children' ASVs and CO_2 levels at the time of filling out the questionnaire are significantly correlated during non-heating seasons (Spearman correlation coefficient = 0.17, $P < .001$); however, the correlation is less significant during heating seasons (Spearman correlation coefficient = 0.10, $P < .01$). CO_2 measurements are recorded at 5-min intervals in this study; therefore, "at-the-time CO_2 level" refers to the average CO_2 levels during the last 5 minutes. Correlations suggest that the strength of the relationship between CO_2 levels and ASVs is higher during non-heating (17%) than heating seasons (10%).

Correlations between ASVs and CO_2 levels were compared with the average of CO_2 levels during the last 10 and 15 minutes of the survey to estimate which range of CO_2 better indicates children's perception of IAQ, Table 8. During non-heating seasons, the correlation between ASVs and 5-minute CO_2 levels (correlation coefficient = 0.17) is higher than that with an average of 10-minute (correlation coefficient = 0.15) or 15-minute (correlation coefficient = 0.14) CO_2 measurements. During heating seasons, the correlation between ASVs and 5-min CO_2 levels ($P = .01$, correlation coefficient = 0.10) is more significant than that with average of 10-minute CO_2 measurements ($P = .04$, correlation coefficient = 0.09) and it is not significant for 15-minute CO_2 ($P = .25 > 0.05$), Table 8. Children' ASVs and average CO_2 levels during the whole session were not correlated ($P = .41 > .05$). Correlation coefficient shows the strength of the relationship between a pair of variables[71,72];

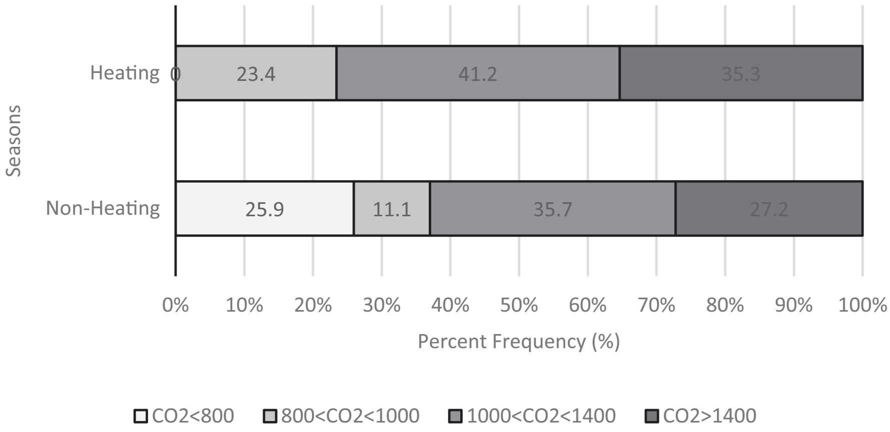


FIGURE 5 Frequency (%) of "at-the-time CO_2 levels" in each category of IAQ during different seasons

TABLE 7 Mean and SD of T_{op} in each category of IAQ

Categories	CO_2 levels	Percent frequency (%)	T_{op} (Mean)	T_{op} (SD)
Category I	<800	14.7	23.31	3.01
Category II	$800 < CO_2 < 1000$	16.5	22.93	2.26
Category III	$1000 < CO_2 < 1400$	38.1	22.94	1.93
Category IV	$CO_2 > 1400$	30.7	22.88	1.13

TABLE 8 The correlation between ASVs and 5-, 10-, and 15-min averages of CO_2 levels

Seasons	CO_2 level	Sig. (2-tailed) with ASVs	Correlation with ASVs
Non-heating	5-min average	0.000	0.172***
	10-min average	0.000	0.148***
	15-min average	0.000	0.142***
Heating	5-min average	0.018	0.103*
	10-min average	0.042	0.089*
	15-min average	0.251	0.050

*$P < .05$.
**$P < .01$.
***$P < .001$.

therefore, the last 5-minutes CO_2 measurements are used for further analysis due to a stronger relationship with ASVs.

The stronger relationship between ASVs and "5-minute CO_2 measurement" than "10 or 15 minutes CO_2 measurement" suggests that children get adapted to indoor CO_2 levels after 5 minutes. After 5-minute adaptation, children's ASVs in this study are independent of CO_2 levels. Similar studies support that due to adaptation, ASVs show high acceptability, and adapted subjects would not distinguish between high and low levels of concentration.[79,80] The study by Cain (1985) found that after 3 minutes of adaptation, perceived intensity reaches a stable level of 40% of the initial amount.[81] Another study by Gunnarsen (1992) shows that 95% of the votes on IAQ change due to adaptation which took place within 6 minutes of exposure.[79] After 5 minutes, adapted votes that are independent of CO_2 levels are obtained; therefore, the study uses at-the-time CO_2 levels (5-min measurement) for further analysis. Standards and regulations usually consider average CO_2 levels as an indicator of IAQ because concentrations are generally spatially non-uniform.[28] However, these results suggest that children's instantaneous perception of IAQ is more related to CO_2 levels at the time of the survey. Therefore, children's ASVs in short intervals should also be evaluated to have a better understanding of perceived IAQ.

3.2.2 | Degree of variations (regressions)

For each survey, the proportions of "very fresh/fresh" (ie, ASV = 1 or 2), "OK" (ie, ASV = 3), and "stuffy/very stuffy" (ie, ASV = 4 or 5) votes were calculated and plotted against CO_2 levels during non-heating and heating seasons, Figures 6 and 7. Similarly, the proportion of children who prefer the air quality to be "fresher" (ie, APV = 1) or "as it is" (ie, APV = 2) was calculated and plotted against CO_2 levels, Figures 6 and 7.

Non-heating seasons: As can be seen in Figure 6, by the increase in CO_2 levels, "fresh/very fresh" votes decrease, and "OK" and "stuffy/very stuffy" votes increase during non-heating seasons. Regressions in Figure 6 suggest that 33% variations in "fresh/very fresh" votes, 28% variations in "OK" votes and 5% variations in "stuffy/very stuffy" votes are explained by CO_2 levels. To predict how votes change by CO_2 changes, "slope" and "intercept" of each linear model are also considered, as suggested in other studies.[71,72] Slopes in Figure 6 show that the rate at which CO_2 changes affect ASVs is highest for "fresh/very fresh" votes, then "OK" votes and then "stuffy/very stuffy" votes during non-heating seasons.

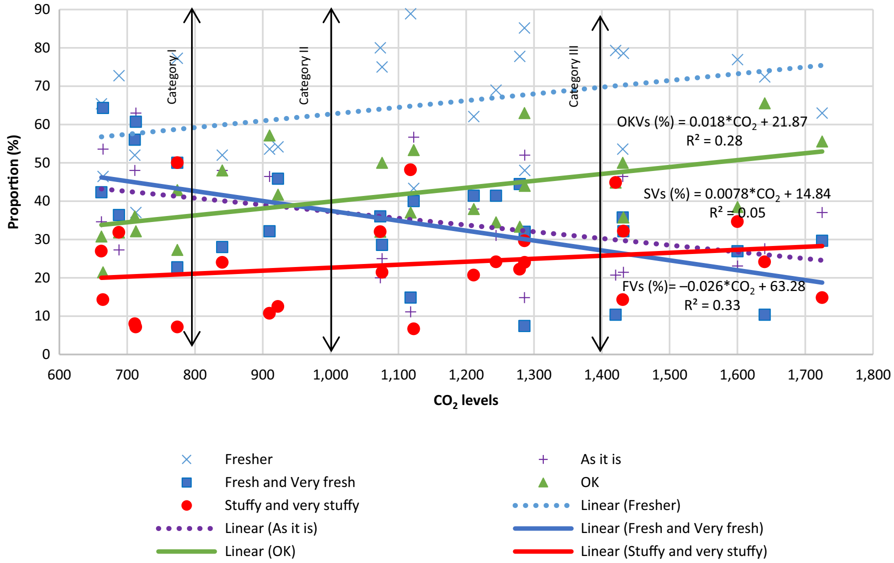


FIGURE 6 Proportions of ASVs and APVs by CO_2 levels during non-heating seasons

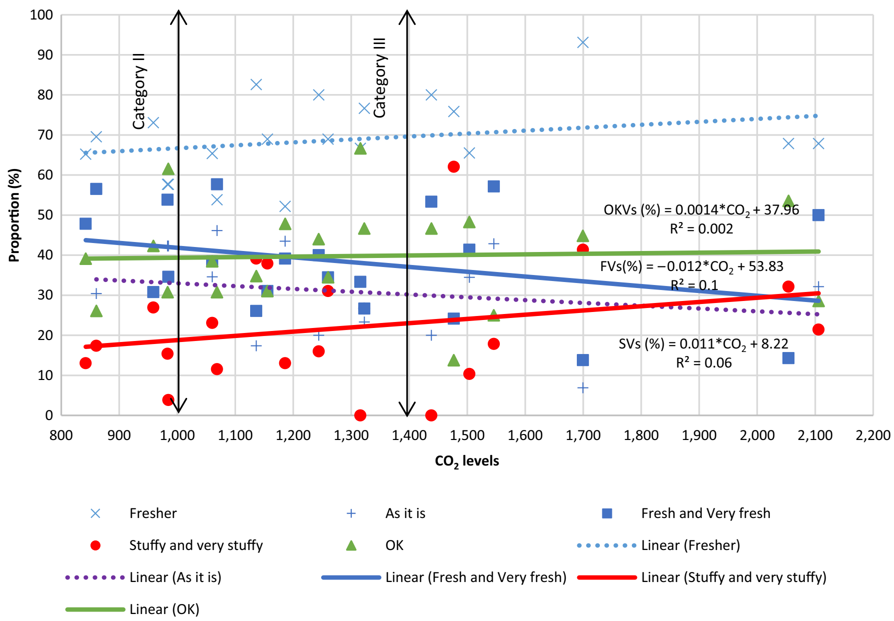


FIGURE 7 Proportions of ASVs and APVs by CO_2 levels during heating seasons

Figure 6 shows that “fresh/very fresh” line intersects with “OK” line at CO_2 level of 950 ppm and it intersects with “stuffy/very stuffy” line at CO_2 level of 1450 ppm. This indicates that at CO_2 = 950 ppm, the proportion of “fresh/very fresh” and “OK” votes is equal and at CO_2 level = 1450 ppm, the proportion of “fresh/very fresh” and “stuffy/very stuffy” votes is equal. When CO_2 > 950 ppm, the proportion of “OK” votes is more than “fresh/very fresh” votes, and when CO_2 > 1450 ppm, the proportion of “stuffy/very stuffy” votes is more than “fresh/very fresh” votes. This suggests that “at-the-time CO_2 levels” should not exceed 1450 ppm; otherwise, the proportion of “stuffy/very stuffy” votes would be more than “fresh/very fresh” votes. CO_2 level of 1450 ppm is close to the upper limit of Category III buildings which corresponds to a moderate level of expectation for existing buildings.

Heating Seasons: As can be seen in Figure 7, by the increase in CO_2 levels, “fresh/very fresh” votes decrease, “OK” votes do not change, and “stuffy/very stuffy” votes increase during non-heating seasons. Regressions in Figure 7 reflect that only 10% variations in “fresh/very fresh” votes, 6% variations in “stuffy/very stuffy” votes, and 2% variations in “OK” votes are explained by CO_2 levels. Slopes in Figure 7 show that the rate of CO_2 changes is highest for “fresh/very fresh” votes, then “stuffy/very stuffy” votes, and then “OK” votes during heating seasons. The graph shows that “fresh/very fresh” line intersects with “OK” line at CO_2 level = 1150 ppm and it intersects with “stuffy/very stuffy” line at CO_2 = 2000 ppm. This shows that at CO_2 = 1150 ppm, the proportion of “fresh/very fresh” and “OK” votes is equal and at CO_2 = 2000 ppm, the proportion of “fresh/very fresh” and “stuffy/very stuffy” votes is equal.

Comparing Figures 6 and 7 shows that the proportion of "OK" votes increases by the increase in CO_2 during non-heating seasons; however, they do not change significantly during the heating season. This suggests that "OK" votes do not show a fixed or recognized trend for acceptability on air sensation scale. On the other hand, "OK" votes on thermal sensation scale are perceived acceptable because thermal sensation scale is symmetrical with more acceptable votes in the middle and less acceptable ones at the ends. Air sensation scale has a direction from the acceptable to unacceptable votes, with "OK" votes in the middle as a transition point. Therefore, only "fresh/very fresh" and "stuffy/very stuffy" votes change by CO_2 variations.

3.2.3 | CO_2 levels and Predicted Percentage Dissatisfied (PPD)

European[21] and ASHRAE standards[14] suggest that for acceptable *IAQ*, the percentage of dissatisfaction among occupants should not be more than 20%.[14,82-84] Maximum PPD of 20% regarding thermal comfort is generally acceptable; therefore, it is prudent to adopt a 20% PPD level regarding IAQ.[20]

EN 13779:2007[62] for categories I and II and ASHRAE standards[14] recommend CO_2 levels below 1000 ppm for maintaining IAQ; this level is also recommended in several other studies.[15] Therefore, PPD is calculated for CO_2 levels more than 1000 ppm or less than 1000 ppm, Figure 8. Results of this study show that when CO_2 < 1000 ppm, expected percentage dissatisfied (PPD) with IAQ is 17.4%. Two more studies confirm that the threshold for PPD of 20% is approximately 1000 ppm.[20] When CO_2 > 1000 ppm, "stuffy/very stuffy" votes increase around 9% and "fresh/very fresh" votes decrease around 13%. This means by keeping CO_2 levels below 1000 ppm, around 22% improvement in ASVs can be maintained. Furthermore, when CO_2 < 1000 ppm, "Fresh/Very Fresh" votes are 27% higher than "Stuffy/Very Stuffy" votes; however, this difference is only 5% when CO_2 > 1000 ppm.

3.3 | Impact of operative temperature and humidity on ASVs

Humphreys et al (2002) suggest that physical variables such as air temperature and relative humidity affect IAQ perception directly.[85] Wargocki and Wyon (2017) also show that the mechanisms that mediate the impacts of IAQ and thermal environment on performance are surprisingly similar.[86] To discover how operative temperature (T_{op}), humidity (RH%), and ASVs are related, correlation tests were run between ASVs, $T_{op,}$ and RH%, Table 9. Previous studies have shown that lower humidity improves perceived IAQ [28,81,87,88]; however, results of this study show that humidity does not affect children's ASVs ($P_{(NH)}$ = 0.072 and $P_{(H)}$ = 0.46 > 0.05), Table 9. This is mainly because children are not exposed to very low or very high humidity levels in this study (38%-66% during non-heating and 26%-53% during heating seasons), Table 6. It is also shown that humidity has a modest effect on thermal sensation and perceived IAQ for moderate environments (<26°C)[89] activity levels (<2 met).[21,89] As can be seen in Table 9, there is a correlation between CO_2 levels and humidity during non-heating (Spearman correlation coefficient = 0.11, P < .005) and heating seasons (Spearman correlation coefficient = 0.43, P < .001). This is mainly because relative humidity and CO_2 levels are both emanated through occupants' respiration and sweating, as suggested by Ghita and Catalina (2015)[90]; therefore, relative humidity and CO_2 variations have similar patterns.

Results of this study show that operative temperature (T_{op}) is not correlated to children's ASVs during non-heating seasons (P = .27 > .05); however, it is significantly related to their ASVs during heating seasons (Spearman correlation coefficient = 0.15, P < .001), Table 9. During non-heating seasons, ASVs are correlated to CO_2 levels (Spearman correlation coefficient = 0.172, P < .001) and not to T_{op} (P = .27 > 0.05), Table 9. During heating seasons, ASVs are more correlated to T_{op} (Spearman correlation coefficient = 0.15, P < .001) compared to CO_2 levels (Spearman correlation coefficient = 0.1, P < .05), Table 9. To assure that

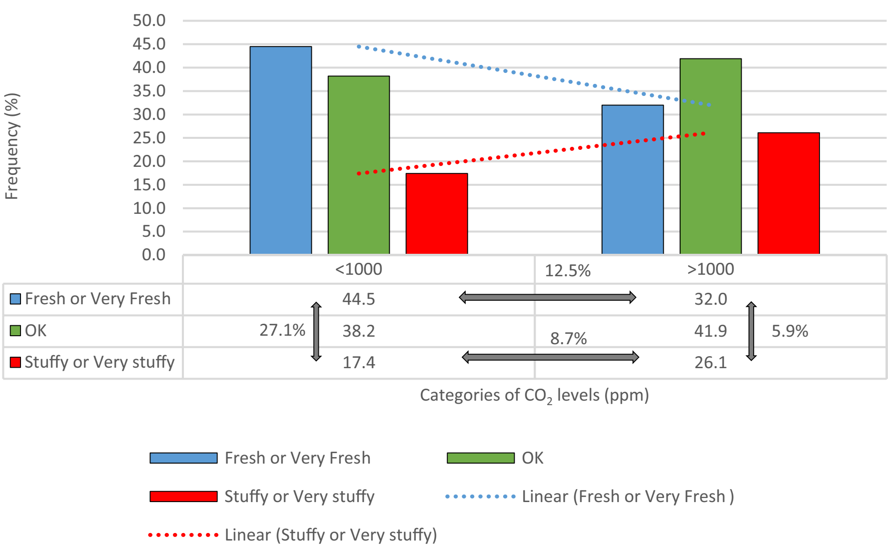


FIGURE 8 Frequency (%) of ASVs in each category of IAQ

TABLE 9 The correlation coefficient between parameters

		ASVs		Operative temperature (T_{op})		Humidity (RH%)	
Seasons	Parameters	Correlation	Sig.	Correlation	Sig.	Correlation	Sig.
Non-heating	ASVs	1.000	.	0.04	0.27	−0.067	0.072
	CO_2 level	0.172***	0.000	-0.12***	0.002	0.11	0.004
Heating	ASVs	1.000	.	0.15***	0.000	−0.03	0.46
	CO_2 level	0.10*	0.018	-0.10*	0.026	0.43	0.000

*$P < .05$.
**$P < .01$.
***$P < .001$.

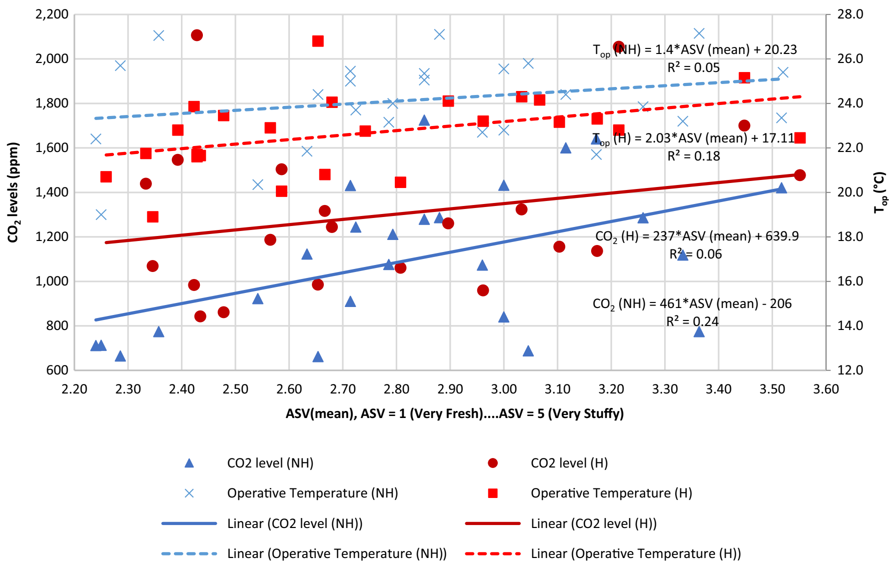


FIGURE 9 Impact of CO_2 levels (ppm) and T_{op} (°C) on mean ASVs

impact of T_{op} on ASVs is not influenced by CO_2 levels, the correlation between CO_2 levels and T_{op} is also investigated in Table 9. Results show that CO_2 and T_{op} have a negative correlation; suggesting that the impact of T_{op} on ASVs is not skewed by CO_2 levels. The negative correlation between CO_2 levels and T_{op} (°C) in this study is due to more open windows during non-heating seasons compared to heating seasons.

Children's mean ASVs are calculated for each survey based on scale codes in Table 2 (very fresh = 1, fresh = 2, OK = 3, stuffy = 4, very stuffy = 5). Figure 9 shows the relationship between mean ASVs for each survey, CO_2 levels (ppm), and T_{op} (°C) at the time of filling out the questionnaire. As can be seen in Figure 9, by an increase in CO_2 levels and T_{op}, mean ASVs increase. Regressions in Figure 9 suggest that 24% and 6% variations in ASVs are explained by CO_2 levels during non-heating and heating seasons, respectively. Similarly, 5% and 18% variations in ASVs are explained by T_{op} during non-heating and heating seasons, respectively. Results of the study show that for 1°C increase in T_{op} (°C), ASVs increase 0.8 and 0.5 points on the 5-point rating scale during non-heating and heating seasons. For 200 ppm increase in CO_2 levels, ASVs increase 0.45 and 0.85 points during non-heating and heating seasons. A similar study shows that by 1°C change in room temperature, average ASV of university students changes 0.3-0.4 points on the 6-point rating scale.[19]

Results of this study show that lower temperatures improve children's perception of IAQ. Previous studies have also confirmed that lower temperature (keeping the air cool) improves perceived IAQ and higher temperatures degrade IAQ.[28,30,81,87,91,92] Therefore, the air is perceived fresher at reduced temperatures and stuffier at higher temperatures. Temperature changes the energy content of the air and the cooling effect in the respiratory tract.[88] When the temperature is considerably lower than the mucosal temperature (30-32°C), the thermal sense is stimulated due to convective and evaporative cooling of the respiratory tract.[15] When the respiratory cooling effect decreases to a certain level, the air is perceived very poor whether the air is clean or polluted.[88] A similar study shows that for the median indoor temperature of 22.31°C, students were totally satisfied with IAQ while for temperatures greater than 25°C, they were dissatisfied.[33] Thermal conditions can also affect IAQ indirectly by influencing emission sources and indoor concentrations of pollutants.[12]

Figure 10 shows that the impact of temperature on ASVs *decreases* with an increasing level of CO_2 concentration. As can be seen in Figure 10, when CO_2 level = 800 ppm, by 1°C decrease in temperature from 24.5°C to 23.5°C, children's ASVs change from "stuffy/very stuffy" to "fresh/very fresh." However, when CO_2 level > 1400 ppm, a decrease in temperature does not change or improve children's ASVs significantly. Figure 11 shows that the influence of CO_2 concentration on ASVs decreases with increasing temperature. As can be seen in Figure 11, when $T_{op} = 19°C$, around 300 ppm decrease in CO_2 level from 1500 to 1200 ppm improves children's ASVs from "stuffy/very stuffy" to "fresh/very fresh." However, when $T_{op} > 26°C$, the decrease in CO_2 levels does not significantly improve children's ASVs.

This study shows that the impact of temperature on ASVs *decreases* with increasing CO_2 levels, and the influence of CO_2 concentration on ASVs decreases with increasing temperature. Both findings are supported in a similar study by Fang et al (1998)[88] on the impact of temperature and humidity on the perception of IAQ. These findings can be explained by two reasons; warm air can be interpreted stuffy and perceived unacceptable, whether the air is fresh or stuffy.[88] It is shown that temperature affects IAQ especially when the air is overheated.[88] Stuffy air can also be interpreted as warm in the respiratory tract and perceived unacceptable.[88,93]

3.3.1 | Comfort temperature

An earlier study by authors shows that the upper limit of thermal comfort band for surveyed children is around 23°C.[94] Therefore, the *frequency (%)* of ASVs in two categories of operative temperature ($T_{op} < 23°C$ and $T_{op} > 23°C$) is investigated. The result of the chi-square test shows that there is a significant difference in the frequency of ASVs in two categories of operative temperatures [$X^2(2, N = 1359) = 19.9, P < .001$]. As can be seen in Figure 12, when $T_{op} < 23°C$, "Fresh/Very Fresh" votes are around 9% higher and "Stuffy/very stuffy" votes are around 11% lower compared to when $T_{op} \geq 23°C$. Therefore, around 20% *improvement* in ASVs can be observed when T_{op} is within or lower than children's thermal comfort band. Furthermore, when $T_{op} < 23°C$, "Fresh/Very Fresh" votes are 25% higher than "Stuffy/Very Stuffy" votes; however, this difference is only 5% when $T_{op} > 23°C$.

To ensure that children's improved perception of IAQ is also impacted by lower temperatures and not merely by air change rates, ventilation rates, and CO_2 levels, the study considers the correlation between operative temperatures, air change rates, and ventilation rates. An earlier study by authors[95] evaluates ventilation rates on the same classrooms from the transient mass balance method. Results show that T_{op} is correlated with ACRs (Spearman correlation coefficient = 0.20, $P < .05$) and VRs (Spearman correlation coefficient = 0.29, $P < .001$). The positive correlation suggests that when T_{op} is higher, ACRs and VRs are also higher.[95] This indicates that by the increase of T_{op}, there is a higher tendency to open windows which in turn increases VRs, as supported in several other studies.[22,42]

This finding rejects the hypothesis that lower temperatures improve children's perception of IAQ through higher ventilation rates.

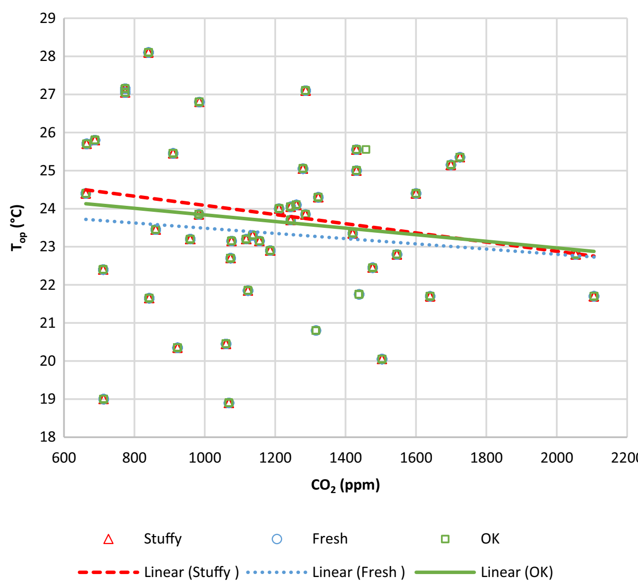


FIGURE 10 Impact of temperature on ASVs with increasing CO_2 level

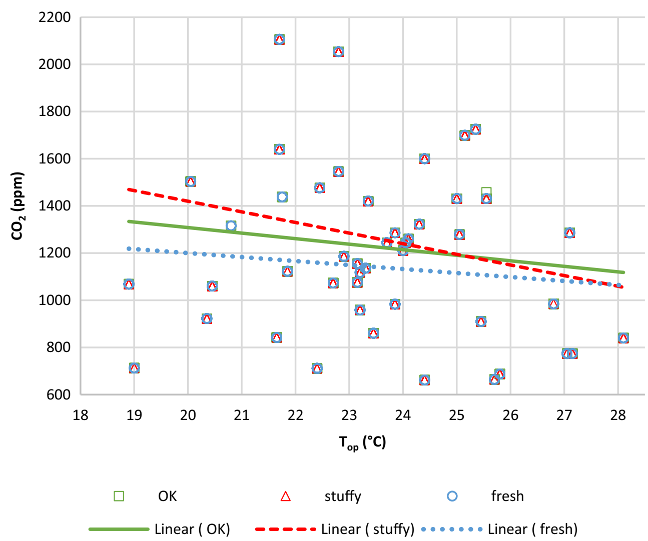


FIGURE 11 Impact of CO_2 levels on ASVs with increasing temperature

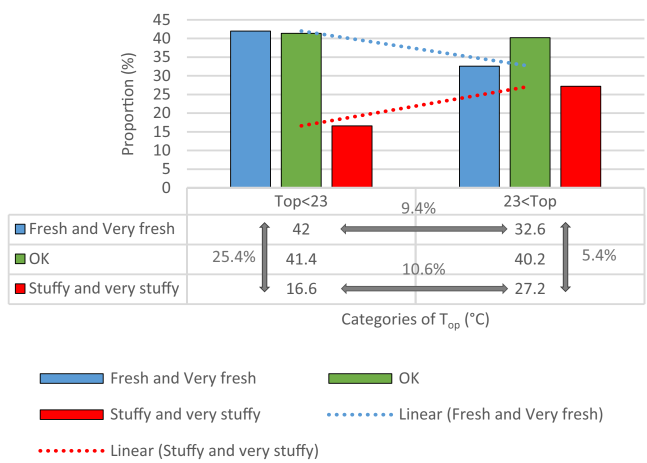


FIGURE 12 The effect of T_{op} (°C) on ASVs

The study highlights that lower temperatures improve children's perception of IAQ independent of ventilation rates.

3.4 | Impact of thermal perception on ASVs

The study shows the effect of TSVs and TPVs on ASVs in boxplots, Figures 13 and 14. Results of Kruskal-Wallis H test show that there is a statistically significant difference in mean and median of ASVs between different groups of TSVs during non-heating ($\chi^2(4) = 26.89$, $P = .000$) and heating ($\chi^2(4) = 58.97$, $P = .000$) seasons. Similarly, there is a statistically significant difference in ASVs between different groups of TPVs during non-heating ($\chi^2(4) = 62.13$, $P = .000$) and heating ($\chi^2(4) = 61.2$, $P = .000$) seasons.

Figure 13 shows that children's ASVs are oriented toward stuffy/very stuffy votes when children feel hot [$ASV_{(mean)}$ = 3.3-3.5] and cold [$ASV_{(mean)}$ = 2.6-3.2]. This finding is confirmed by Humphreys et al (2002) that show when occupants are uncomfortably warm, they perceive IAQ poorly.[85] The most favorable ASVs [$ASV_{(mean)}$ = 2.4-2.5] are given when children feel "cool" during both seasons. Figure 14 shows that when children have "cooler" preference, they give the least favorable ASVs [$ASV_{(mean)}$ = 3.4]; however, when they have "as it is" preference, they give the most favorable ASVs [$ASV_{(mean)}$ = 2.4-2.5]. Humphreys et al (2002) also support that respondents give the most favorable ASVs when they require no change in the thermal environment.[85] Therefore, in this study with the focus on UK children, the most favorable ASVs are given when children feel "cool" and have "as it is" preference. However, these results may be different in another climate.

In Table 10, *crosstabs* were created by using TSVs, TPVs, and ASVs. Among children who feel "hot," nearly half of them (47%) find the classroom "stuffy/very stuffy," while less than a quarter (23%) find the classroom "fresh/very fresh." Among children who feel "cool," more than half of them (53%) find the classroom "fresh/very fresh" and only 13% find the classroom "stuffy/very stuffy"; "fresh/very fresh" votes are 4 times more than "stuffy/very stuffy" votes, Table 10.

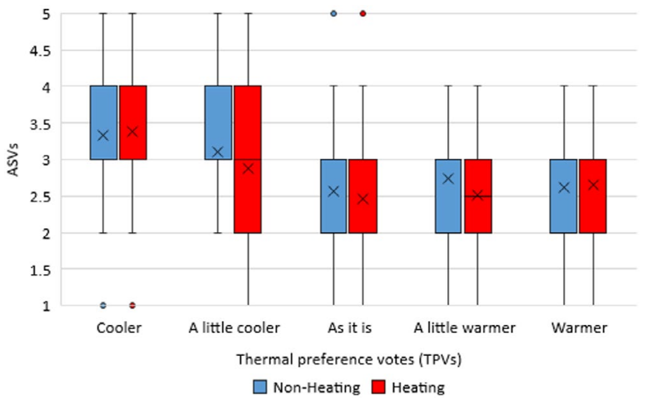


FIGURE 14 ASVs change within different categories of TPVs

Among children who have "cooler" preference, 23% find the classroom "fresh/very fresh" and 48% find the classroom "stuffy/very stuffy"; "stuffy/very stuffy" votes are more than two times "fresh/very fresh" votes, Table 10. Among children who prefer the classroom "as it is," 46% find the classroom "fresh/very fresh" and 8% find the classroom "stuffy/very stuffy"; "fresh/very fresh" votes are 5.8 times more than "stuffy/very stuffy" votes, Table 10. This indicates the impact of TSVs and TPVs on ASVs; when children are more satisfied with their thermal environment, they give more favorable ASVs.

3.5 | Integration

Results of this study show that by keeping CO_2 levels below 1000 ppm, ASVs improve by 23% (Refer to 3.1.3). Furthermore, by keeping operative temperatures within or below thermal comfort band (T_{op} < 23°C in this study), ASVs improve by around 20%. To integrate the impact of both T_{op} and CO_2 on ASVs, the proportion of children in each category of ASVs based on T_{op} and CO_2 is presented in Table 11.

According to Table 11, when CO_2 < 1000 ppm and T_{op} < 23°C (operative temperature is below the upper limit of thermal comfort

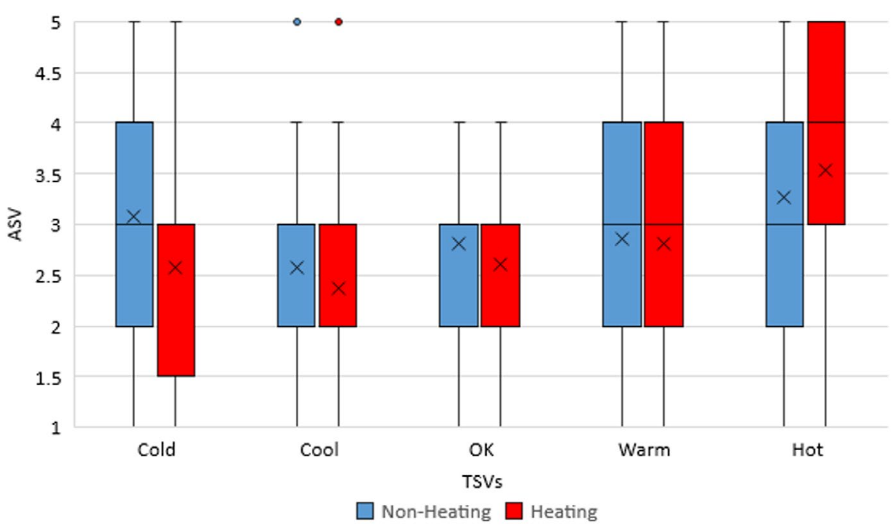


FIGURE 13 ASVs change within different categories of TSVs

TABLE 10 Frequency of TSVs and TPVs in each category of ASVs

TSVs/TPVs		Air quality							
		Very fresh		Fresh		Stuffy		Very stuffy	
		Number	%	Number	%	Number	%	Number	%
TSVs	Cold	12	21.8	8	14.5	9	16.4	6	10.9
	Cool	30	15.0	75	37.5	22	11.0	4	2.0
	OK	44	8.9	133	26.8	66	13.3	7	1.4
	Warm	47	11.7	96	23.8	97	24.1	13	3.2
	Hot	14	6.9	33	16.2	50	24.5	45	22.1
TPVs	Cooler	24	9.7	34	13.7	69	27.8	50	20.2
	A little cooler	24	6.9	72	20.8	95	27.5	11	3.2
	As it is	52	12.0	146	33.6	34	7.8	3	0.7
	A little warmer	26	11.7	69	30.9	29	13.0	6	2.7
	Warmer	21	19.6	24	22.4	17	15.9	5	4.7

TABLE 11 Frequency (%) of children' ASVs based on T_{op} and CO_2

CO_2 level (ppm)	Top	ASVs	Percent (%)
<1000	Top < 23°C	Fresh or very fresh	53.0
		OK	37.0
		Stuffy or very stuffy	10.0
	Top > 23°C	Fresh or very fresh	41.4
		OK	38.6
		Stuffy or very stuffy	20.0
>1000	Top < 23°C	Fresh or very fresh	36.7
		OK	41.4
		Stuffy or very stuffy	21.9
	Top > 23°C	Fresh or very fresh	28.7
		OK	42.2
		Stuffy or very stuffy	29.1

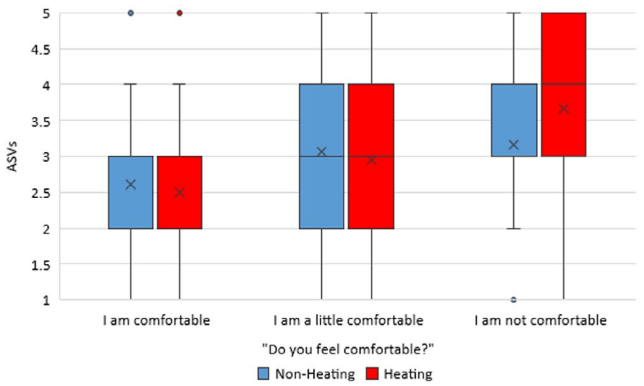


FIGURE 15 ASV changes in different comfort groups

band), only 10% of children find the classroom "stuffy/very stuffy," which is lower than PPD recommended by EN 15251 [21] for Category I buildings. A similar study[15] estimates that keeping CO_2 < 1000 ppm and T_{op} < 22°C can reduce PPD to 15%.[15] Table 11 shows that when CO_2 < 1000 ppm and T_{op} > 23°C, PPD increases to 20%. Another study[15] estimates that when CO_2 < 1000 ppm and T_{op} > 26°C, PPD will rise to 25%.[15] Table 11 shows when CO_2 > 1000 ppm and T_{op} > 23°C, 29.1% of children find the classroom "stuffy/very stuffy." When "CO_2 < 1000 ppm & T_{op} < 23°C" compared to when "CO_2 > 1000 ppm & T_{op} > 23°C," "stuffy/very stuffy" votes are 19% less and "fresh/very fresh" votes are 24% more (43% improvements on ASVs).

Improving ASVs by 43% is hard to achieve just by lowering CO_2 levels and increasing ventilation rates; therefore, decreasing operative temperatures within thermal comfort band can also help to improve children's perception of IAQ. The study by Bakó-Biró et.al (2012) recommends UK schools managers to consider CO_2, temperature, and humidity for maintaining IAQ, to keep temperatures within comfortable ranges [20-22°C during winter] and [22-24°C during summer] and humidity levels below 60% during winter time but preferably above 40%.[96] The study by Chatzidiakou et al (2015) confirms the need for an integrated approach providing simultaneously adequate IAQ and thermal comfort[15] to improve the perception of IAQ. There is evidence that in case of insufficient cooling, increasing ventilation rate would be a waste of energy without any improvement in environment; however, decreasing air temperature up to the comfort threshold would succeed to provide a more pleasant perception of IAQ.[88] Fanger (1998) suggests ventilation standards such as ASHRAE do not consider the impact of temperature and humidity on perceived IAQ.[88] The review by Salthammer et al (2016) shows that poor IAQ in schools can be related to lack of budgets for local administrative bodies and inefficiency of regulations for better IAQ.[97] Results of this study also suggest that standards and regulations should consider the integrated impact of both temperature and CO_2 levels on perceived IAQ.

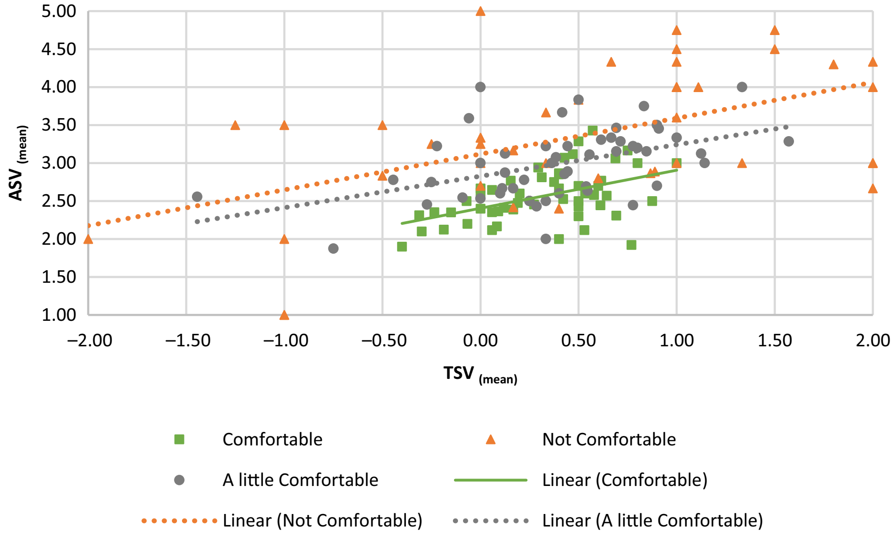
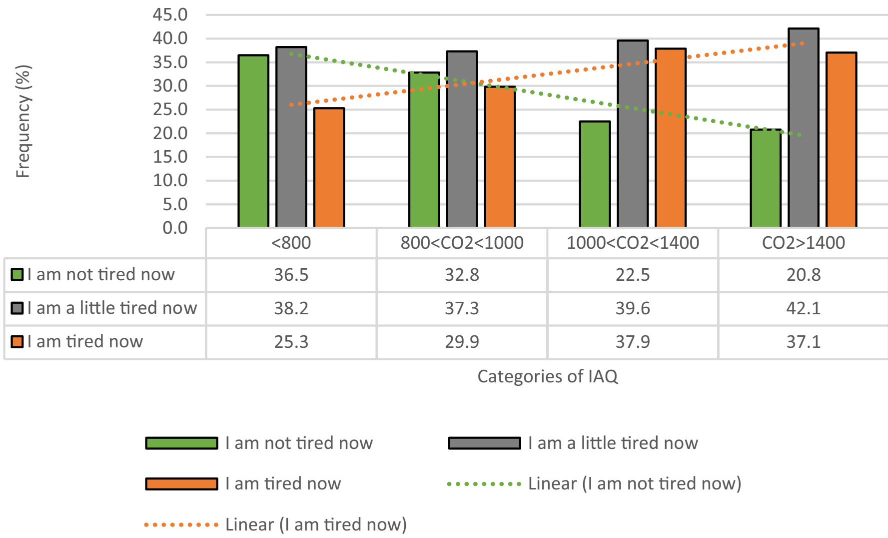


FIGURE 16 The combined effect of ASVs and TSVs on different comfort levels



	<800	800<CO2<1000	1000<CO2<1400	CO2>1400
I am not tired now	36.5	32.8	22.5	20.8
I am a little tired now	38.2	37.3	39.6	42.1
I am tired now	25.3	29.9	37.9	37.1

FIGURE 17 Frequency (%) of children in each group of tiredness for IAQ categories

3.6 | The impact of TSVs and ASVs on overall comfort

The study examines the effect of ASVs on different comfort groups as boxplots in Figure 15. Results of Kruskal-Wallis H test show that there is a statistically significant difference in mean and median of ASVs between different comfort groups during non-heating ($\chi^2(4) = 48.5$, $P = .000$) and heating ($\chi^2(4) = 104.5$, $P = .000$) seasons. Results show that when children are comfortable, mean ASVs are the most favorable ($ASV_{NH} = 2.6$, $ASV_H = 2.4$) and when children are not comfortable, mean ASVs are the least favorable ($ASV_{NH} = 3.2$, $ASV_H = 3.7$), Figure 15.

To examine the combined effect of ASVs and TSVs on comfort level, classrooms' mean ASVs and TSVs for each comfort group are presented in Figure 16. As can be seen in Figure 16, range of TSVs and ASVs for "comfortable" children is narrower than that for "a little comfortable" and "uncomfortable" children. Figure 16 shows that TSVs range from "−0.4 to +1" for comfortable votes, while they range from "−2 to +2" for uncomfortable votes. The difference between the range of TSVs for comfortable and uncomfortable votes is 2.6 [(−2 to 2) - (−0.4 to 1)]. On the other hand, ASVs range from "+2.2 to +2.9" for comfortable votes, while they range from "+2.2 to +4" for uncomfortable votes. The difference between the range of ASVs for comfortable and not comfortable votes is 1.1 [(4-2.2) - (2.9-2.2)]. This suggests that changes in TSVs compared to ASVs are more significant in different *comfort* groups.

3.7 | Impact of CO_2 levels, ASVs, and TSVs on Tiredness

The frequency (%) of children in each group of tiredness for different IAQ categories is depicted in Figure 17. The result of chi-square test shows that there is a significant difference in frequency of (%) of tiredness groups in four categories of IAQ [$X^2(6, N = 1216) = 26.2$, $P < .001$]. Figure 17 shows that as classrooms' IAQ deteriorates from Category I to IV, the proportion of children feeling not tired decreases around 16% and the proportion of children feeling tired

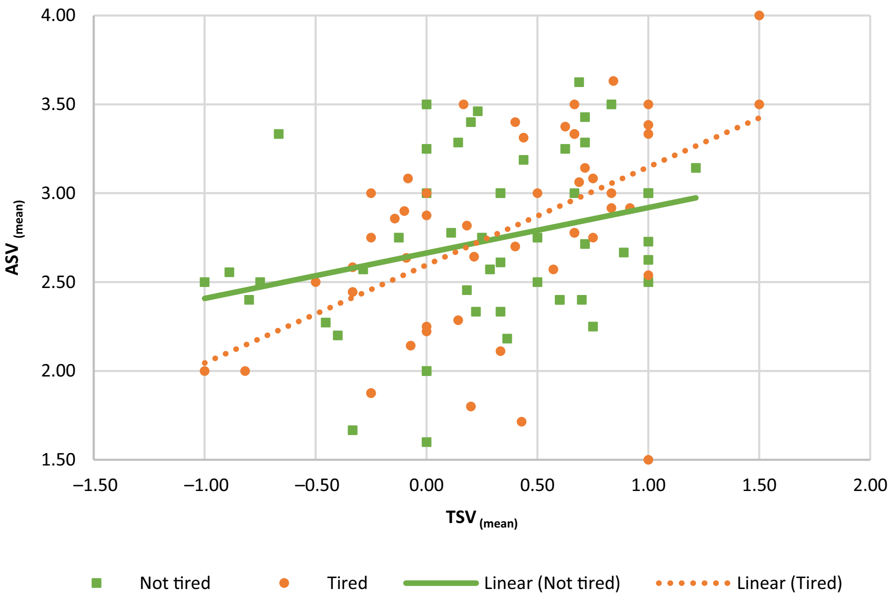


FIGURE 18 The combined effect of ASVs and TSVs on different levels of tiredness

increases around 12%. In total, by improving classrooms' IAQ from Category IV to I, 28% of tiredness votes can be improved.

To examine the combined effect of ASVs and TSVs on tiredness level, classrooms' mean ASVs and TSVs for each tiredness group are presented in Figure 18. As shown in Figure 18, TSVs range from "−1 to +1.25" for the "not-tired" group, while it ranges from "−1 to +1.5" for the "tired" group. The difference between ranges of TSVs for tired and not-tired groups is 0.25 [(−1 to 1.5) - (−1 to 1.25)]. On the other hand, ASVs range from "+2.5 to +3" for the "not-tired" group, while they range from "+2 to +3.5" for the "tired" group. The difference between the range of ASVs for "not-tired" and "tired" groups is 1.1 [(3.5-2) - (3-2.5)]. This suggests that changes in ASVs compared to TSVs are more significant in different groups of *tiredness*.

This study shows that by the increase in CO_2 levels, tiredness levels increase. Previous studies have also shown that higher CO_2 levels are related to higher tiredness[29,65,96] and discomfort[7,65] levels. It is important to reduce the CO_2 level before discomfort and tiredness levels set in. An earlier study by authors using the same data set[65] highlights that high CO_2 levels in classrooms impact children's errors in responding; therefore, among children who provide invalid and inconsistent responses to questionnaires, around 80% are tired or a little tired. It is shown that at concentrations over 1000 ppm, failures in decision making start to show and that at 2500 ppm failure in decision making is clear.[31] Coley et al (2007) show that in classrooms where CO_2 levels are high, students are less attentive and cannot concentrate well on what the teacher is saying, which over time can have detrimental effects on their learning performance.[32] CO_2 is seen as a harmless gas and is given little significance[96]; however, as it contributes directly to the loss of concentration and increased tiredness,[98] it should be regarded as a very significant air pollutant.[96] By lowering CO_2 levels and improving IAQ, children would feel more comfortable and less tired,[7,65,96] which can consequently increase their productivity and learning performance.[31,99] The importance of ensuring acceptable IAQ in classrooms is distinguished as a contributing factor to the learning performance of students.[100] Mechanisms that mediate the effects of thermal conditions and IAQ on performance are similar[86]; therefore, it is expected to improve both collectively.

4 | CONCLUSION

This paper has focused on factors influencing children's perception of IAQ in primary school classrooms during non-heating and heating seasons. The study suggests that children's perception of IAQ depends on "at-the-time CO_2 level" which refers to the last 5 minutes of CO_2 measurement because children adapt to the classroom's IAQ after 5 minutes. Therefore, studying CO_2 levels within short intervals reflects children's perception of IAQ more reliably than looking at average CO_2 levels.

This study also highlights that indoor operative temperature and perception of the thermal environment (T_{op} and TSVs) impact children's perception of IAQ. High temperatures and children's poor perception of thermal environment reduce children's acceptance of IAQ, even when CO_2 levels are within acceptable limits. Low CO_2 levels fail to provide acceptable IAQ when children are thermally uncomfortable in classrooms. According to results of this study, children's perception of IAQ deteriorates significantly when CO_2 level goes above 1000 ppm and the operative temperature goes above the upper limit of thermal comfort band (above 23°C in this study). When CO_2 < 1000 ppm and T_{op} < 23°C, only 10% of children have "Stuffy/Very stuffy" votes, while this amount triples when CO_2 > 1000 ppm and T_{op} > 23°C. These findings urge school stakeholders and especially building management systems (BMS) to control CO_2 levels and indoor operative temperatures collectively to improve children's perception of IAQ. Standards and regulations should also consider both CO_2 levels and T_{op} to evaluate IAQ.

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CONFLICT OF INTEREST

The authors declare that no conflict of interest could be perceived as prejudicing the impartiality of the research reported.

AUTHOR CONTRIBUTIONS

Sepideh Sadat Korsavi: Conceptualization (lead); Data curation (lead); Formal analysis (lead); Investigation (lead); Methodology (lead); Visualization (lead); Writing-original draft (lead); Writing-review & editing (lead). **Azadeh Montazami:** Conceptualization (supporting); Funding acquisition (lead); Resources (lead); Supervision (lead); Visualization (equal); Writing-review & editing (equal). **Dejan Mumovic:** Visualization (supporting); Writing-review & editing (supporting).

NOMENCLATURE

Symbols

T_{op}	Operative Temperature (°C)
V	Air Speed (m/s)
CO_2	CO2 level
RH	Relative Humidity (%)
P-value	Significance of correlation Coefficient
R^2	Coefficient of Determination

Abbreviations

Cor, Correlation; Sig., Significance of correlation Coefficient; No., Number; Vo, Volume; Orn, Orientation.

Parameters

IAQ	Indoor Air Quality
TSV(s)	Thermal Sensation Vote(s)
ASV(s)	Air Sensation Vote(s)
SD	Standard Deviation
PPD	Predicted Percentage Dissatisfied
NV	Naturally Ventilated
WA	Window Area
NW	Number of Windows
MHW	Minimum Height of Windowsill
ACRs	Air Change Rates
VRs	Ventilation Rates

PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1111/ina.12740.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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REFERENCES

1. Hou Y, Liu J, Li J. Investigation of indoor air quality in primary school classrooms. *Procedia Eng*. 2015;121:830-837. https://doi.org/10.1016/j.proeng.2015.09.037
2. Luther MB, Horan P, Tokede O. Investigating CO2 concentration and occupancy in school classrooms at different stages in their life cycle. *Archit Sci Rev*. 2017;61:83-95. https://doi.org/10.1080/00038628.2017.1416576
3. De Giuli V, Da Pos O, De Carli M. Indoor environmental quality and pupil perception in Italian primary schools. *Build Environ*. 2012;56:335-345. https://doi.org/10.1016/j.buildenv.2012.03.024
4. Daisey JM, Angell WJ, Apte MG. Indoor air quality, ventilation and health symptoms in schools: an analysis of existing information. *Indoor Air*. 2003;13:53-64. https://doi.org/10.1034/j.1600-0668.2003.00153.x
5. Stabile L, Dell M, Russi A, Massimo A, Buonanno G. The effect of natural ventilation strategy on indoor air quality in schools. *Sci Total Environ*. 2017;595:894-902. https://doi.org/10.1016/j.scitotenv.2017.03.048
6. Toftum J, Kjeldsen BU, Wargocki P, Menå HR, Hansen EMN, Clausen G. Association between classroom ventilation mode and learning outcome in Danish schools. *Build Environ*. 2015;92:494-503. https://doi.org/10.1016/j.buildenv.2015.05.017
7. Johnson DL, Lynch RA, Floyd EL, Wang J, Bartels JN. Indoor air quality in classrooms: Environmental measures and effective ventilation rate modelling in urban elementary schools. *Build Environ*. 2018;136:185-197. https://doi.org/10.1016/j.buildenv.2018.03.040
8. Building Bulletin 101: Guidelines on ventilation, thermal comfort and indoor air quality in schools, Department for Education and Skills, DfES London, 2016.
9. Kamaruzzaman S, Razak R. Measuring indoor air quality performance in Malaysian Government Kindergarden. *J Build Perform*. 2011;2:70-79.
10. Maxwell LE. A safe and welcoming school: What students, teachers, and parents think. *J Archit Plann Res*. 2000;17:271-282.
11. Zomorodian ZS, Tahsildoost M, Hafezi M. Thermal comfort in educational buildings: A review article. *Renew Sustain Energy Rev*. 2016;59:895-906. https://doi.org/10.1016/j.rser.2016.01.033
12. Chatzidiakou L, Mumovic D, Summerfield AJ. What do we know about indoor air quality in school classrooms? A critical review of the literature. *Intell Build Int*. 2012;4:228-259. https://doi.org/10.1080/17508975.2012.725530
13. Shendell DG, Prill R, Fisk WJ, Apte MG, Blake D, Faulkner D. Associations between classroom CO2 concentrations and student attendance in Washington and Idaho. *Indoor Air*. 2004;14:333-341. https://doi.org/10.1111/j.1600-0668.2004.00251.x
14. ASHRAE 2106, Ventilation for acceptable indoor air quality. ANSI/ASHRAE Standard 62.1., 2016.
15. Chatzidiakou L, Mumovic D, Summerfield A. Is CO2 a good proxy for indoor air quality in classrooms? Part 2: Health outcomes and

perceived indoor air quality in relation to classroom exposure and building characteristics. *Build Serv Eng Res Technol*. 2015;36:162-181. https://doi.org/10.1177/0143624414566245

16. Bakó-biró Z, Clements-croome DJ, Kochhar N, Awbi HB, Williams MJ. Ventilation rates in schools and pupils ' performance. *Build Environ*. 2012;48:215-223. https://doi.org/10.1016/j.buildenv.2011.08.018
17. Chatzidiakou L, Mumovic D, Summerfield A. Is CO2 a good proxy for indoor air quality in classrooms? Part 1: The interrelationships between thermal conditions, CO2 levels, ventilation rates and selected indoor pollutants. *Build Serv Eng Res Technol*. 2015;36:129-161. https://doi.org/10.1177/0143624414566244
18. Astolfi A, Pellerey F. Subjective and objective assessment of acoustical and overall environmental quality in secondary school classrooms. *J Acoust Soc Am*. 2008;123:163-173. https://doi.org/10.1121/1.2816563
19. Norbäck D, Nordström K. An experimental study on effects of increased ventilation flow on students' perception of indoor environment in computer classrooms. *Indoor Air*. 2008;18:293-300. https://doi.org/10.1111/j.1600-0668.2008.00530.x
20. Lugg AB, Batty WJ. Air quality and ventilation rates in school classrooms I: Air quality monitoring. *Build Serv Eng Res Technol*. 1999;20:13-21.
21. CEN (European Committee for Standardization), EN 15251: *Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics*. Eur. Comm. Stand. 3. London: British Standards Institution;2007:54.
22. Santamouris M, Synnefa A, Asssimakopoulos M, et al. Experimental investigation of the air flow and indoor carbon dioxide concentration in classrooms with intermittent natural ventilation. *Energy Build*. 2008;40:1833-1843. https://doi.org/10.1016/j.enbuild.2008.04.002
23. Olesen BW. International standards for the indoor environment. *Indoor Air*. 2004;14(s7):18-26. https://doi.org/10.1111/j.1600-0668.2004.00268.x
24. Turanjanin V, Vučićević B, Jovanović M, Mirkov N, Lazović I. Indoor CO2 measurements in Serbian schools and ventilation rate calculation. *Energy*. 2014;77:290-296. https://doi.org/10.1016/j.energy.2014.10.028
25. Peters A, Dockery DW, Heinrich J, Wichmann HE. Short-term effects of particulate air pollution on respiratory morbidity in asthmatic children. *Eur Respir J*. 1997;10:872-879.
26. Fraga S, Ramos E, Martins A, et al. Indoor air quality and respiratory symptoms in Porto schools. *Rev Port Pneumol*. 2008;14:487-507. https://doi.org/10.1016/s2173-5115(08)70277-x
27. Liu MM, Wang D, Zhao Y, et al. Effects of outdoor and indoor air pollution on respiratory health of Chinese children from 50 kindergartens. *J Epidemiol*. 2013;23:280-287. https://doi.org/10.2188/jea.JE20120175
28. Seppänen OA, Fisk WJ, Mendell MJ. Association of ventilation rates and CO2 concentrations with health and other responses in commercial and institutional buildings. *Indoor Air*. 1999;9:226-252.
29. Myhrvold AN, Olsen E, Lauridsen O. Indoor environment in schools–pupils health and performance in regard to CO2 concentrations. *Indoor Air*. 1996;96:369-371.
30. Wargocki P, Wyon DP. Providing better thermal and air quality conditions in school classrooms would be cost-effective. *Build Environ*. 2013;59:581-589. https://doi.org/10.1016/j.buildenv.2012.10.007
31. Satish U, Mendell MJ, Shekhar K, et al. Is CO2 an indoor pollutant? Direct effects of low-to-moderate CO2 concentrations on human decision-making performance. *Environ Health Perspect*. 2012;120:1671-1677.
32. Coley DA, Greeves R, Saxby BK. The effect of low ventilation rates on the cognitive function of a primary school class. *Int J Vent*. 2007;6:107-112. https://doi.org/10.1080/14733315.2007.11683770
33. Dorizas PV, Assimakopoulos M, Santamouris M. A holistic approach for the assessment of the indoor environmental quality, student productivity, and energy consumption in primary schools. *Environ Monit Assess*. 2015;187:259-277. https://doi.org/10.1007/s10661-015-4503-9
34. Berner MM. Building conditions, parental involvement, and student achievement in the District of Columbia public school system. *Urban Educ*. 1993;28:6-29.
35. Lee SC, Chang M. Indoor and outdoor air quality investigation at schools in Hong Kong. *Chemosphere*. 2000;41(1–2):109-113. https://doi.org/10.1016/S0045-6535(99)00396-3
36. Vilcekova S, Meciarova L, Burdova EK, Katunska J, Kosicanova D, Doroudiani S. Indoor environmental quality of classrooms and occupants' comfort in a special education school in Slovak Republic. *Build Environ*. 2017;120:29-40. https://doi.org/10.1016/j.buildenv.2017.05.001
37. Godoi RHM, Avigo D, Campos VP, et al. Indoor air quality assessment of elementary schools in Curitiba, Brazil. *Water Air Soil Pollut Focus*. 2009;9:171-177.
38. Batterman S, Su FC, Wald A, Watkins F, Godwin C, Thun G. Ventilation rates in recently constructed US school classrooms. *Indoor Air*. 2017;27(5):880-890. https://doi.org/10.1111/ina.12384
39. Peled R. Air pollution exposure: who is at high risk? *Atmos Environ*. 2011;45:1781-1785.
40. Buonanno G, Morawska L, Stabile L, Wang L, Giovinco G. A comparison of submicrometer particle dose between Australian and Italian people. *Environ Pollut*. 2012;169:183-189.
41. Selgrade MK, Plopper CG, Gilmour MI, Conolly RB, Foos BSP. Assessing the health effects and risks associated with children's inhalation exposures—asthma and allergy. *J Toxicol Environ Heal Part A*. 2007;71:196-207.
42. Almeida RMSF, De Freitas VP. Indoor environmental quality of classrooms in Southern European climate. *Energy Build*. 2014;81:127-140. https://doi.org/10.1016/j.enbuild.2014.06.020
43. Katafygiotou MCC, Serghides DKK. Indoor comfort and energy performance of buildings in relation to occupants' satisfaction: investigation in secondary schools of Cyprus. *Adv Build Energy Res*. 2014;8:216-240. https://doi.org/10.1080/17512549.2013.865554
44. Nam I, Yang J, Lee D, Park E, Sohn J. A study on the thermal comfort and clothing insulation characteristics of preschool children in Korea. *Build Environ*. 2015;92:724-733. https://doi.org/10.1016/j.buildenv.2015.05.041
45. Wargocki P, Wyon DP. The effects of outdoor air supply rate and supply air filter condition in classrooms on the performance of schoolwork by children (RP-1257). *HVAC&R Res*. 2007;12:165-191.
46. Dascalaki EG, Sermpetzoglou VG. Energy performance and indoor environmental quality in Hellenic schools. *Energy Build*. 2011;43:718-727. https://doi.org/10.1016/j.enbuild.2010.11.017
47. Nicol F, Humphreys M, Roaf S. *Adaptive thermal comfort: principles and practice*. London: Routledge; 2012.
48. Oppenheim AN. *Questionnaire Design, Interviewing and Attitude Measurement*. UK: Bloomsbury Publishing. 2000.
49. Gilani S, O'Brien W. Review of current methods, opportunities, and challenges for in-situ monitoring to support occupant modelling in office spaces. *J Build Perform Simul*. 2017;10(5–6):444-470. https://doi.org/10.1080/19401493.2016.1255258
50. Gratia E, Bruyere I, De Herde A. How to use natural ventilation to cool narrow office buildings. *Build Environ*. 2004;39:1157-1170.

51. Mumovic D, Wilton O, Hong S-M. *Designing Natural Ventilation for Urban Buildings. In A Handbook of Sustainable Building Design and Engineering*. London: Routledge; 2018:290-316.
52. Levermore GJ. The exponential limit to the cooling of buildings by natural ventilation. *Build Serv Eng Res Technol*. 2002;32(2):119-125. https://doi.org/10.1191/0143624402bt032oa
53. Corgnati SP, Ansaldi R, Filippi M. Thermal comfort in Italian classrooms under free running conditions during mid seasons: Assessment through objective and subjective approaches. *Build Environ*. 2009;44:785-792. https://doi.org/10.1016/j.buildenv.2008.05.023
54. Teli D, Jentsch MF, James PABB. Naturally ventilated classrooms: An assessment of existing comfort models for predicting the thermal sensation and preference of primary school children. *Energy Build*. 2012;53:166-182. https://doi.org/10.1080/09613218.2013.773493
55. Weather Observations Website, (2017). http://wow.metoffice.gov.uk/http://wow.metoffice.gov.uk/ (accessed December 20, 2017)
56. Building bulletin 93. A design guide: Acoustic design for schools, 2003.
57. Extrium, England Noise Map Viewer (2015). http://www.extrium.co.uk/noiseviewer.html
58. CIBSE TM 21, Minimising pollution at air intakes, 1999.
59. Metoffice, Pollution Forecast, UK AIR Air Inf. Resour. (2017). https://uk-air.defra.gov.uk/forecasting/index
60. Heebøll A, Wargocki P, Toftum J. Window and door opening behavior, carbon dioxide concentration, temperature, and energy use during the heating season in classrooms with different ventilation retrofits—ASHRAE RP1624. *Sci Technol Built Environ*. 2018;24:626-637. https://doi.org/10.1080/23744731.2018.1432938
61. Ozkutuk A, Ceylan E, Ergor G, et al. The relationship between moulds isolated from indoor air and features of the house environment. *Indoor Built Environ*. 2008;17:269-273.
62. CEN (European Committee for Standardization), EN 13779. Ventilation for Non-Residential Buildings – Performance Requirements for Ventilation and Room- Conditioning Systems, 2007.
63. Borgers N, De Leeuw E, Hox J. Children as respondents in survey research: cognitive development and response quality. *Bull Methodol Sociol*. 2000;66:60-75. https://doi.org/10.1093/jpepsy/25.1.56
64. Fabbri K. *Indoor thermal comfort perception: A questionnaire approach focusing on children*, New York City, NY, USA: Springer, 2015.
65. Korsavi SS, Montazami A. Developing a valid method to study adaptive behaviours with regard to IEQ in primary schools. *Build Environ*. 2019;153:1-16. https://doi.org/10.1016/j.buildenv.2019.02.018
66. Ramalho O, Mandin C, Ribéron J, Wyart G. Air stuffiness and air exchange rate in French schools and day-care centres. *Int J Vent*. 2013;12:175-180. https://doi.org/10.1080/14733315.2013.11684013
67. Cao A, Ouyang Q, Zhu Y, Huang L, Hu H, Deng G. Development of a multivariate regression model for overall satisfaction in public buildings based on field studies in Beijing and Shanghai. *Build Environ*. 2012;47:394-399. https://doi.org/10.1016/j.buildenv.2011.06.022
68. Fanger PO. Introduction of the olf and the decipol units to quantify air pollution perceived by humans indoors and outdoors. *Energy Build*. 1988;12:1-6. https://doi.org/10.1016/0378-7788(88)90051-5
69. Goto T, Toftum J, De Dear R. Thermal sensation and comfort with transient metabolic rates. *Indoor Air*. 2002;1:1038-1043.
70. ISO Standard 7726. Ergonomics of the thermal environment — Instruments for measuring physical quantities, 2001.
71. Bryman A, Cramer D. *Quantitative data analysis with IBM SPSS 17, 18 and 19*. London: Routledge; 2011.
72. Bryman A, Cramer D. *Quantitative data analysis with SPSS 12 and 13: A guide for social scientists*. London: Psychology Press; 2005.
73. Mccrum-gardner E. Which is the correct statistical test to use? *Br J Oral Maxillofac Surg*. 2008;46(1):38-41. https://doi.org/10.1016/j.bjoms.2007.09.002
74. Marshall E, Boggis E. The statistics tutor's quick guide to commonly used statistical tests. Statstutor Community Project. 2016;1-57.
75. IBM Corp. *IBM SPSS Statistics for Windows*, *Version 24.0*. Armonk, NY: IBM Corp; 2016.
76. Evans JD. *Straightforward statistics for the behavioral sciences*. USA: Thomson Brooks/Cole Publishing Co. 1996.
77. Chan YH. Biostatistics 102: quantitative data–parametric & non-parametric tests. *Singapore Med J*. 2003;44:391-396.
78. ASHRAE. ASHRAE Standard 55-2017 Thermal Environmental Conditions for Human Occupancy, 2017.
79. Gunnarsen L, Ole Fanger P, Fanger PO. Adaptation to indoor air pollution. *Environ Int*. 1992;18(1):43-54.
80. Zhang X, Wargocki P, Lian Z, Xie J, Liu J. Responses to human bioeffluents at levels recommended by ventilation standards. *Procedia Eng*. 2017;205:609-614. https://doi.org/10.1016/j.proeng.2017.10.415
81. Cain W. Perception of odor intensity and the time course of olfactory adaptation. *ASHRAE Trans*. 1985;80:53-75.
82. Hui PS, Wong LT, Mui KW. Using carbon dioxide concentration to assess indoor air quality in offices. *Indoor Built Environ*. 2008;17:213-219. https://doi.org/10.1177/1420326X08091773
83. Mui KW, Wong LT. Evaluation of the neutral criterion of indoor air quality for air-conditioned offices in subtropical climates. *Build Serv Eng Res Technol*. 2007;28:23-33. https://doi.org/10.1177/0143624406070666
84. Lai ACK, Mui KW, Wong LT, Law LY. An evaluation model for indoor environmental quality (IEQ) acceptance in residential buildings. *Energy Build*. 2009;41:930-936. https://doi.org/10.1016/j.enbuild.2009.03.016
85. Humphreys MA, Nicol JF, McCartney KJ. An analysis of some subjective assessments of indoor air-quality in five European countries. *Indoor Air*. 2002;5:86-91.
86. Wargocki P, Wyon DP. Ten questions concerning thermal and indoor air quality effects on the performance of office work and schoolwork. *Build Environ*. 2017;112:359-366. https://doi.org/10.1016/j.buildenv.2016.11.020
87. Berglund LG, Cain W. Perceived air quality and the thermal environment. *Proc IAQ*. 1989;89:93-99.
88. Fang L, Clausen G, Fanger PO. Impact of temperature and humidity on the perception of indoor air quality. *Indoor Air*. 1998;8:80-90. https://doi.org/10.1111/j.1600-0668.1998.t01-2-00003.x
89. ISO Standard 7730. Ergonomics of the thermal environment Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria, Int. Organ. Stand. Geneva. 2005.
90. Ghita SA, Catalina T. Energy efficiency versus indoor environmental quality in different Romanian countryside schools. *Energy Build*. 2015;92:140-154. https://doi.org/10.1016/j.enbuild.2015.01.049
91. Cain WS, Leaderer BP, Isseroff R, et al. Ventilation requirements in buildings—I. Control of occupancy odor and tobacco smoke odor. *Atmos Environ*. 1983;17:1183-1197.
92. Seppanen OA, Fisk WJ. Summary of human responses to ventilation. *Indoor Air*. 2004;14(s7):102-118.
93. Toftum J, Jørgensen AS, Fanger PO. Effect of humidity and temperature of inspired air on perceived comfort. *Energy Build*. 1998;28:15-23.

94. Korsavi SS, Montazami A. Children's thermal comfort and adaptive behaviours; UK primary schools during non-heating and heating seasons. *Energy Build*. 2020;214:109857. https://doi.org/10.1016/j.enbuild.2020.109857
95. Korsavi SS, Montazami A, Mumovic D. Ventilation rates in naturally ventilated primary schools in the UK; Contextual, Occupant and Building-related (COB) factors. *Build Environ*. 2020;181:107061.
96. Bakó-Biró Z, Clements-Croome DJ, Kochhar N, Awbi HB, Williams MJ. Ventilation rates in schools and pupils' performance. *Build Environ*. 2012;48:215-223. https://doi.org/10.1016/j.buildenv.2011.08.018
97. Salthammer T, Uhde E, Schripp T, et al. Children's well-being at schools: Impact of climatic conditions and air pollution. *Environ Int*. 2016;94:196-210. https://doi.org/10.1016/j.envint.2016.05.009
98. Kajtár L, Herczeg L, Láng E, Hrustinszky T, Bánhidi L. Influence of carbon-dioxide pollutant on human well-being and work intensity, in: HB 2006 - Heal. Build. Creat. a Heal. Indoor Environ. People, Proc., 2006: pp. 85-90.
99. Wyon A, Wargocki P, Toftum J, Clausen G. Classroom ventilation must be improved for better health and learning. *REHVA Eur HVAC J*. 2010;3:12-16.
100. Alwetaishi MS. Impact of building function on thermal comfort: A review paper. *Am J Eng Appl Sci*. 2016;9:928-945. https://doi.org/10.3844/ajeassp.2016.928.945

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