energies
MDPI
Article

Investigation and Evaluation of Winter Indoor Air Quality of Primary Schools in Severe Cold Weather Areas of China

Fusheng Ma [1,2], Changhong Zhan [1,*] and Xiaoyang Xu [2]

1 School of Architecture, Harbin Institute of Technology and Key Laboratory of Cold Region Urban and Rural Human Settlement Environment Science and Technology, Ministry of Industry and Information Technology, Harbin 150001, China; mfs1973@163.com
2 Construction Technology Research Institute, Shenyang Jianzhu University, Shenyang 110168, China; xuxiaoyang1206@hotmail.com
* Correspondence: zhan.changhong@hit.edu.cn; Tel.: +86-0-13945109451

Received: 3 April 2019; Accepted: 24 April 2019; Published: 26 April 2019

check for updates

Abstract: The indoor air quality (IAQ) in classrooms has attracted more and more attention. Unfortunately, there is limited information relating to IAQ in the primary schools in severe cold weather areas of China. In this study, a field investigation on the IAQ of a primary school of Shenyang in northeast China was carried out by physical measurements and questionnaire surveys. The carbon dioxide (CO_2) concentration in selected classrooms was continuously measured for a week, and the corresponding ventilation rate was calculated. Meanwhile, the perceptions of the IAQ, the purpose and the comfort degree of window opening have also been recorded from 106 pupils, aged 9–12. The results indicate the ventilation rate is considerably inadequate in about 99% of the class time due to the low frequency of window opening. The average daily CO_2 concentration in these classrooms is 1510–3863 ppm, which is far higher than the recommended value of 1000 ppm. Most pupils understand that the purpose of opening windows in winter is to improve air quality. However, there are big differences between the measurement results and subjective judgments of indoor air quality. Contrary to the high measured CO_2 concentration, around 70% pupils consider the air fresh, and only 3.7% pupils are dissatisfied and even very dissatisfied with IAQ in their classroom. It is necessary to change the existing manual window opening mode, because the pupils' subjective judgment affects the window opening behavior.

Keywords: severe cold areas; primary school; natural ventilation; IAQ; carbon dioxide; ventilation rate

1. Introduction

More and more studies have been written about the indoor air quality (IAQ) in primary and secondary school buildings [1]. The health and performance of occupants are affected by indoor air quality, which affects children more than adults [2–4]. In addition, classrooms are densely occupied environments [5,6], and most students are usually in school for 5–9 hours every weekday [7–10]. Most of this time is spent in the classroom, with long periods of time spent sitting in chairs. Research shows that a good indoor environment can reduce absence rates [11,12] and improve students' learning efficiency [13–16]. The air quality and temperature in the classroom are important factors in the learning process, and improving the air quality and temperature in schools is as important to student success as improving the level of teaching materials and teaching methods [17]. Unfortunately, poor indoor air quality in primary schools has become a global issue, with problems including low ventilation rates, insufficient fresh air, excessive indoor particle and CO_2 concentration levels [6,9,10,18–21].

Many scholars regard CO_2 concentration as a key index for evaluating classroom air quality [21–28]. The method of evaluating indoor air quality based on CO_2 measurement is convenient and inexpensive, and reasonable and accurate measuring and logging instruments can be provided [29]. Moreover, high CO_2 concentration affects adult decision-making performance and neuro- physiological symptom [30,31]. Simultaneously, high CO_2 concentrations are related to students' performance in class, affecting their learning efficiency, health status and absenteeism rate. Twardella et al. [23] showed that low air quality by increasing CO_2 concentration did not reduce students' short-term performance, but the error rate increased. Further, higher CO_2 concentrations can reflect inadequate ventilation. The research of Fisk [1] showed that indoor CO_2 concentrations above 1000 ppm indicate a ventilation rate of less than 7 L/s per person. Bako-Biro et al. [7] found that the CO_2 concentrations in some UK schools were much higher than recommended levels, and that low ventilation rates significantly reduced students' memory and alertness. The findings of Tofum et al. [32] have provided more evidence that inadequate classroom ventilation affects learning outcomes, so that classroom air quality should be a major priority in building or remodeling existing schools. Some studies have shown that the CO_2 concentration in passive ventilation classrooms and mechanical ventilation classrooms exceeds the recommended standard [33,34]; however, the CO_2 concentration under the condition of mechanical ventilation is significantly better than that under the condition of natural ventilation [35,36]. The maximum CO_2 concentration in naturally ventilated classrooms was generally 4–6 times higher than the reference value [7,8,18,20,22,26,27,37,38].

At present, natural ventilation is widely used in primary school buildings in severe cold weather regions of China, even during the winter heating season. This ventilation mode mainly depends on opening windows manually (without any mechanical equipment). The characteristics of China's monsoon climate make cold regions colder in the winter, and the cold is more persistent than in other regions of the world at the same latitude. Thus, the heating intensity in these areas of China is much higher than that of European and American cities located in the same latitude [39]. The demands of energy saving and heat preservation result in insufficient indoor ventilation, which seriously affects the indoor air quality. Some studies have begun to pay attention to the indoor environment of primary and secondary schools in China [40,41]. However, there is a lack of on-site survey data regarding pupils' perception and evaluation of indoor air quality in the primary schools of China's severe cold regions. Correlation analysis between subjective evaluation and objective evaluation is even less available.

This study takes the teaching building of a primary school in Shenyang as the study object. Physical measurements and questionnaire surveys were conducted to investigate and evaluate the indoor air quality of naturally ventilated classrooms during the heating season in this severe cold area. The IAQ and ventilation capacity of three representative classrooms were assessed by means of weekly CO_2 concentration records. During the measurement period, survey questionnaires were implemented to analyze pupils' perception and satisfaction with the IAQ in their classrooms. At the same time, pupils' willingness to open windows in the winter was surveyed through collecting their opinions on the purpose and comfort of window opening. Finally, the differences between the subjective voting about air quality among classes and between genders, the correlation between subjective and objective evaluations, and the influence of subjective perceptions about window opening frequency were analyzed.

2. Case Study

2.1. City Climate

Figure 1 shows that the longitude and latitude of Shenyang in northeast China are 123.38 E and 41.8 N, respectively. In the global climate classification, Shenyang is placed in a region characterized by its temperate semi-humid continental climate. According to the design standard for energy efficiency of public buildings [42], Shenyang belongs to the severe cold area C of China. The heating season in Shenyang lasts for 150 days, from November 1 of each year to April 1 of the following year. The main climate indicator for the severe cold region is the average outdoor temperature of less than −10 °C in January. Meanwhile, the average outdoor temperature is less than 25 °C in July. Therefore, schools in Shenyang are expected to have greater heating than cooling needs throughout the year.

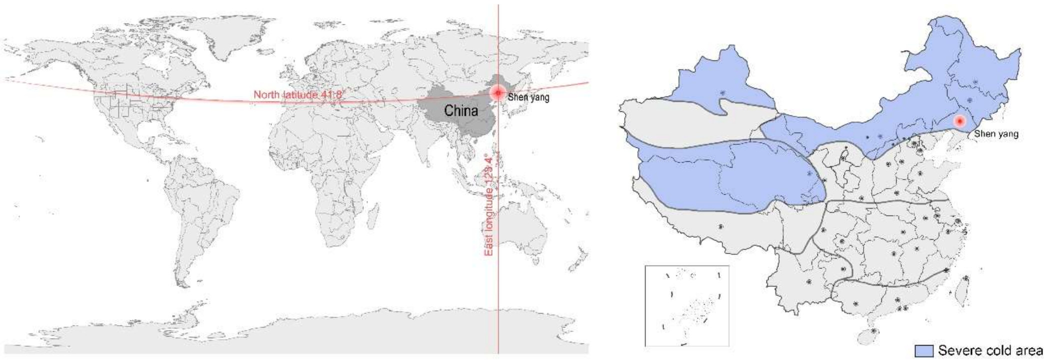


Figure 1. Location of Shenyang and the severe cold area of China.

2.2. Target Building

The naturally ventilated building A of a primary school in Shenyang was selected as a case study (see Figure 2). The building A was constructed in 1999 with six floors, using a reinforced concrete frame construction and brick walls without any thermal insulation materials. The layout, function and space design features of teaching building A are representative of the typical primary and secondary school buildings that have been built in the severe cold regions of China in recent decades. Building A is heated by hot water radiators during the heating season. All classrooms are ventilated by opening windows manually, and there are no mechanical ventilation facilities for use during any part of the year. There are 44 classrooms on the second to fourth floors of the building for grade 4 to grade 6 (pupils aged 8 to 13), of which 28 classrooms face south and 16 classrooms face north. The Building B is also a teaching building for grade 1 to grade 3 (pupils age 6–8).

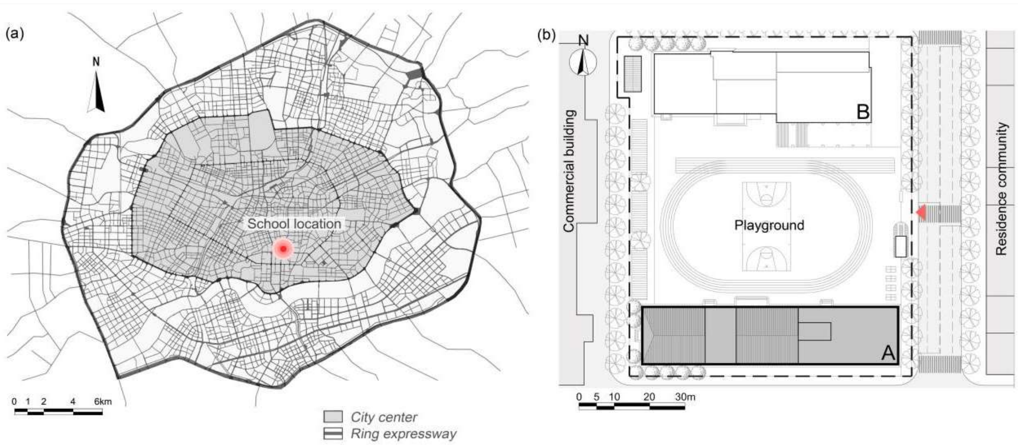


Figure 2. Location of selected primary school in Shenyang City (**a**), Site map (**b**).

2.3. Pupil and Classroom Information

Three 5th grade classrooms on the fourth floor of the teaching building were selected as the research object for data collection; classroom S1(S1) and classroom S2(S2) face south, and classroom N1(N1) faces north (Figure 3). These are representatives of classrooms with different orientations and locations (middle and side), and they house pupils in the same grade for consistency of comparison. Classrooms are typically crowded spaces, especially in China. When school is in session, between 32 and 38 pupils (aged 9 to 12) are present in each classroom. The per capita area of each classroom is 1.43–1.65 m^2, which meets the standard 1.36 m^2/p according to the code for design of school (GB50099-2011) [5], but this is much less than the per capita area of an average classroom in the United States [29] and in European countries [43]. The characteristics of the classrooms studied are presented in Figure 4 and Table 1.

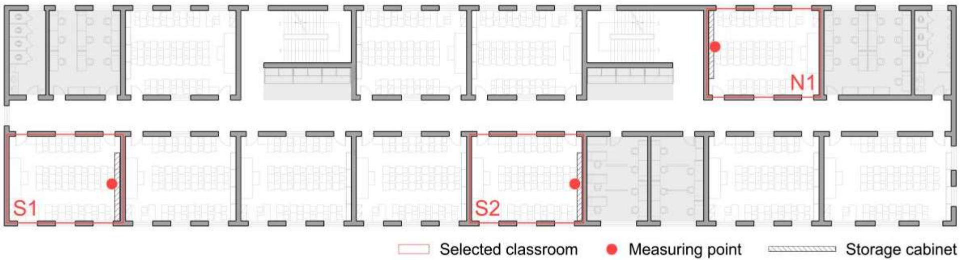


Figure 3. S1, S2 and N1 location on the 4th floor and the measurement points in the classrooms.

Figure 4. Selected classrooms for measurements: (**a**) S1; (**b**) S2; (**c**) N1; (**d**) The corridor in the 4th floor.

Table 1. Characteristics of 4th floor classrooms studied.

Classroom	Orientations	Number	Area	Volume	Exterior Window *	Inner Window **	Doors
		(Boys + Girls)	(m^2)	(m^3)	Size (mm)/Quantity		
S1	South	17 + 16	54.3	173	1800 × 1500/3	900 × 1500/1	2100 × 900/2
S2	South	15 + 23	54.3	173	1800 × 1500/3	900 × 1500/1	2100 × 900/2
N1	North	12 + 24	54.3	173	1800 × 1500/3	900 × 1500/1	2100 × 900/2

* Exterior Window = Window to outdoor, 0.9 m above the ground. ** Inner window = Window to the inner corridor, 1.5 m above the ground.

In China, the pupils will have all their lessons in the same classroom for the whole school term, except the music and experimental classes, which will be in specific music room and outdoor environment, respectively. The curriculum for each class is repeated weekly.

3. Methodology

3.1. Field Measurements

Physical measurements were conducted in three classrooms (one indoor measuring point in each classroom) for a school week (from Monday to Friday), which is shown in Figure 3. The indoor physical parameters were measured by means of field measurements of the following factors: concentration of carbon dioxide (CO_2), air temperature (Ta) and relative humidity of the air (RH). The measured CO_2 concentration and the corresponding ventilation rates were compared with the standards to evaluate the indoor air quality and ventilation capacity of the classrooms, and the corresponding influencing factors were analyzed.

3.1.1. Measurement Instrument and Period

A HOBO (MX 1102) CO_2 logger (Onset, Bourne, MA, USA, Table 2) was used to monitor and collect values of all parameters every 5 min at each measuring point. To determine the best location for the instrument, before any measurements were made, the researchers placed two calibrated measuring instruments in the middle of S1 and on the back storage cabinet for one day to compare the measured data. Comparing the values of the two measurement points, the difference between the CO_2 concentration of the two locations is between ±100 ppm except for a few measurements (which may be disturbed by human activities). The level and trend of CO_2 concentration were similar, which indicates the characteristics of the change in overall CO_2 concentrations were similar in the classroom. Therefore, to minimize interference with the measuring instruments from the environment or by the pupils during the long-term measurement process, the instruments were placed on lockers at the back of three selected classrooms at a height of approximately 1 m above the floor, 2 m away from the windows and doors and 1m from the pupils (see Figure 3). The characteristics of the measuring instruments are presented in Table 2.

Table 2. Instrumentation technical specifications.

Instrument					Measuring		
Name	Type	Parameter	Range	Accuracy	Classroom	Frequency	Response Time
HOBO	MX 1102	CO_2	0–5000 ppm	±50 ppm	S1/S2/N1	5 min	1 min
		Temp.	0–50 °C	±0.21 °C			12 min
		RH	1–90%	±2%			1 min

The measurements were conducted from Monday, March 7th (starting at 07:00) to Friday, March 11th (ending at 18:00) of 2016, and included periods during which the classrooms were both occupied and unoccupied. According to the school's regulations, all classes were conducted from 08:00 to 16:10 from Monday to Friday (Wednesdays from 08:00 to 15:30), but most pupils entered the classroom at 07:30 and left at 16:30. Therefore, the occupied period was defined from 07:30 to 16:30, including periods called Class-Time (C-T) and Intermittent-Time (I-T). Unoccupied periods were defined as part of the time of a school week, except for the occupied periods. The timetable of a regular school day is shown in Table 3.

Class-Time (C-T) refers to the time pupils spend in the classroom according to the school's schedule, including taking courses (such as Chinese, mathematics, art, history, English and other courses) and engaging in self-study.

Table 3. Timetable.

Morning				Noon *	Afternoon			
Activity	**Time**	**Duration (min)**	**Classification**	**Time**	**Activity**	**Time**	**Duration (min)**	**Classification**
Lesson1	8:00–8:40	40	C-T		Lesson5	13:05–13:35	30	C-T
Break1	8:40–8:55	10	I-T		Break4	13:35–13:45	10	I-T
Lesson2	8:55–9:35	40	C-T		Lesson6	13:45–14:15	30	C-T
Break2	9:35–10:15	40	I-T	11:45–13:05	Break5	14:15–15:00	45	I-T
Lesson3	10:15–10:55	40	C-T		Lesson7	15:00–15:30	30	C-T
Break3	10:55–11:10	10	I-T		Break6	15:30–15:40	10	I-T
Lesson4	11:10–11:45	35	C-T		Lesson8	15:40–16:10	30	C-T

* Time for lunch and outdoor activities.

Intermittent-Time (I-T) refers to the time between two C-T periods, including times for breaks, lunch and outdoor activities. The I-T periods of Break 1, 3, 4 and 6 lasting less than 15 mins are called short intervals. Break 2, 5 and Noon lasting 40 mins, 45 mins and 80 mins respectively are called long intervals.

During the measurement period, the frequencies with which doors and windows were opened in the three classrooms were observed and recorded manually. There was almost no window opening behavior in the three classrooms during the periods of C-T. Usually, windows were opened during I-T period by pupils according to their own ideas, but the frequency of window opening was random and short-time.

In fact, for most of the short I-T periods, many pupils stayed in the classrooms instead of going outside. It was difficult to record the changes in occupancy of the classrooms manually, because pupils entered and left the classrooms frequently. Similarly, the frequency of window openings was difficult to capture, because the pupils moved about or gathered in groups in the classrooms. Therefore, the observation data for window openings recorded by the observers may be inaccurate.

3.1.2. Reference Value

The lowest and highest outdoor temperatures during the measured period were obtained from the China Air Quality online Monitoring and Analysis Platform. There are 11 outdoor measurement points for Shenyang city on this platform. The data selected in this paper come from one of the measurement points which is about 3.5 kilometers nearest to the primary school. The range of outside temperatures between 07:00 and 17:00 were as follows: Monday from −4 °C to 2 °C; Tuesday from −7 °C to −1 °C; Wednesday from −7 °C to −1 °C; Thursday from −7 °C to 0 °C; Friday from −11 °C to 2 °C. From Monday to Friday, the outdoor CO_2 concentration was measured by a handheld CO_2 test instrument (Telaire 7001, General Electric Company, Fairfield, Conn, USA) used in the center of the school playground at 7 a.m. and 5 p.m. respectively. The range of outdoor CO_2 concentration varies from 358 to 425 ppm, with an average of 384 ppm. 380 ppm was used as the reference value of outdoor CO_2 concentration in this study. Usually, IAQ is evaluated by means of two main criteria: CO_2 concentration and ventilation rate. In primary schools, 20 m^3/h per person (5.556 L/s per person) is recommended as the minimum ventilation rate, and 1000 ppm as the daily average value of CO_2 concentration [44]. 1080 ppm (700 ppm + outdoor CO_2 concentration 380 ppm) is recommended as the highest value allowed [29].

3.1.3. Formulas for Calculating Ventilation Rate and Variation Rate of CO_2 Concentration

Ventilation rates can be calculated from indoor and outdoor CO_2 measurements over suitable intervals using Equation (1) [25,26]:

$$C_t = C_{ext} + \frac{G}{Q} - (C_{ext} - C_0 + \frac{G}{Q})e^{(-Qt/V)} \quad (1)$$

where C_t is the internal concentration of carbon dioxide at time t (ppm); C_{ext} is the external concentration of carbon dioxide (ppm); G is the generation rate of carbon dioxide in the space (cm^3/s); Q is the internal-external air exchange rate (m^3/s); C_0 is the initial concentration of carbon dioxide (ppm); V is the room volume (m^3); and t is the time (s).

During the unoccupied periods, the value of G is equal to zero. Equation (1) can be expressed as:

$$Q = -\frac{V}{t}\ln(\frac{C_t - C_{ext}}{C_0 - C_{ext}}) \quad (2)$$

The corresponding air exchange rate (AER) is:

$$AER = -\frac{Q}{V} \quad (3)$$

Using the method presented in [26,45], the average CO_2 emission rate per pupil is circa 0.0039 L/s, and that per teacher is circa 0.0054 L/s (The errors of the calculated values between the three classes are very small and can be neglected).

The variation rate (VR) of CO_2 concentration in each C-T period and I-T period is calculated by the difference between the initial and ending CO_2 concentrations during this period:

$$VR = \frac{C_t - C_0}{t} \quad (4)$$

3.2. Questionnaire

During the time in which physical measurements were taken, questionnaire surveys were administered to 106 pupils aged 9–12 in the three study classrooms. The questionnaire design was completed after careful consideration and collaboration with the three classrooms' teachers. That was easily accepted by pupils, because it was written to take into consideration the pupils' levels of understanding, patience, and ability to comprehend technical terms. Details about the questions posed in the survey are shown in Table 3. Through the questionnaire surveys, we can understand the pupils' perception of IAQ and analyze any correlation between perception and the actual CO_2 level and ventilation rate. The voting results also allowed us to assess any possible psychological impacts of indoor air quality on children. Relevant issues have also been raised, such as the reasons of pupils open windows and the comfort level. The information of the questionnaires is as follows: (1) Background information about the pupils such as age, grade, gender and seat position; (2) Indoor air freshness and air quality assessment (i.e., at the moment they completed the questionnaire); (3) Purpose of, and attitude toward, opening windows. The main contents of the questionnaire are shown in Table 4.

Table 4. The survey questionnaire.

1.	How do you feel about the air freshness of your classroom at this moment?			
A. Fresh	B. Stale	C. Stale with Occasional Odor		D. Stale with Odor
2.	How is the air quality in the classroom at this moment?			
A. Very Satisfied	B. Satisfied	C. Neutral	D. Dissatisfied	E. Very Dissatisfied
3.	What is the purpose of opening windows in the winter?			
A. Improve IAQ	B. Reduce Temperature		C. Other	
4.	Do you feel comfortable with a draft caused by opening window?			
A. Very Comfortable	B. Comfortable	C. Neutral	D. Uncomfortable	E. Very Uncomfortable
5.	How do you feel about the temperature in the classroom?			
A. Hot	B. Warm	C. Neither Cool nor Warm	D. Cool	E. Cold
6.	Are you satisfied with the temperature in the classroom?			
A. Very Satisfied	B. Satisfied	C. Neutral	D. Dissatisfied	E. Very Dissatisfied

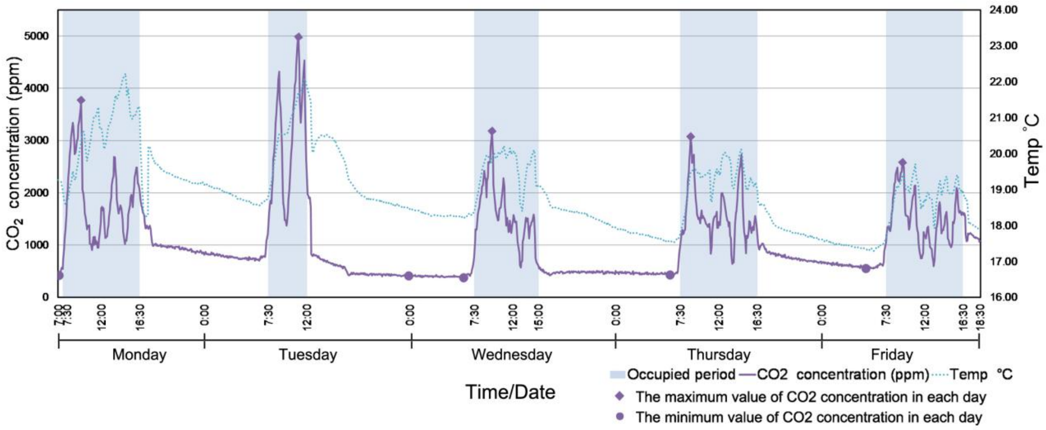
To ensure consistency, the questionnaire was sent out to the pupils at 10:50 on Friday morning (March 11, 2016), which was 10 minutes before the third class was over. At that time, the pupils had been in the classroom for about 30 minutes. The questionnaires were explained by the research team members before the pupils answered them.

The indoor physical conditions of the three classrooms during the questionnaire period were as follows: 1802 ppm (CO_2), 19.4 °C (T_a) and 27.1% (RH) in S1; 1705 ppm (CO_2), 21.9 °C (T_a) and 37.3% (RH) in S2; and 2450 ppm (CO_2), 21.6 °C (T_a) and 39.1% (RH) in N1. The outdoor temperature was 0 °C. 106 pupils answered the questionnaire completely, and their responses were recorded by the researchers.

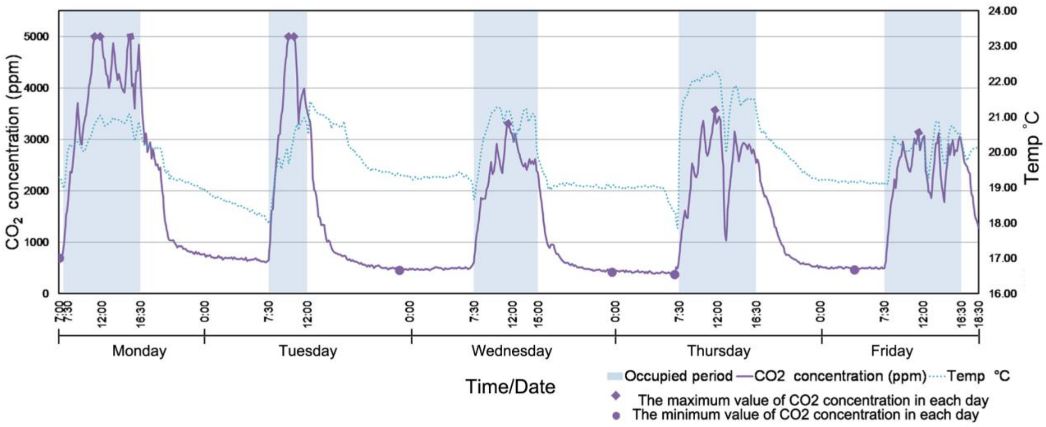
4. Results and Discussion

4.1. Physical Measurement and Analysis

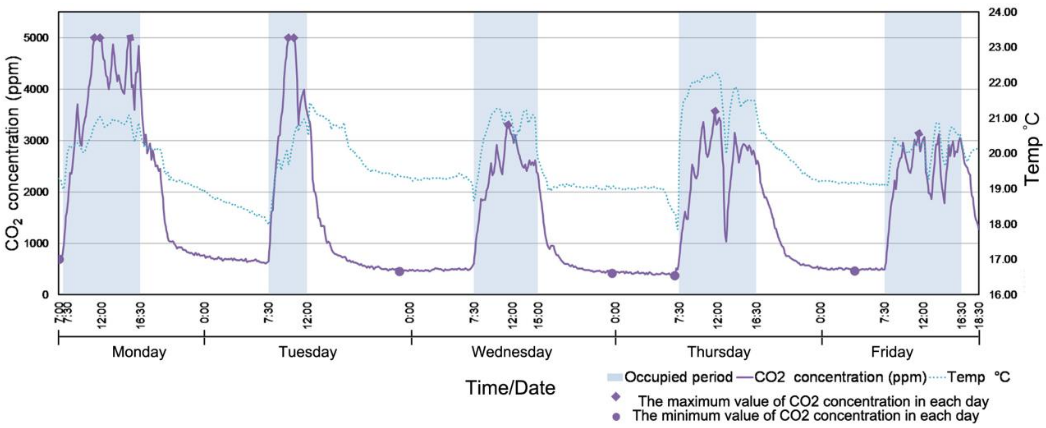
Figure 5a,b,c show a 5-day plot of the CO_2 level and temperature variation in the three classrooms. The CO_2 concentration changed dramatically during the occupied period (grey bars) with a maximum of 5000 ppm and a minimum of 696 ppm. In a closed classroom, the main source of CO_2 was the students' respiration, and its concentration changed with the number of students [8,21]. In this study, pupils start arriving in the classroom after 07:00; the CO_2 levels started to rise when the pupils entered the classroom. The peak period for pupils entering classrooms was between 07:30 and 07:45 every morning. At about 07:45, the CO_2 concentration exceeded 1000 ppm, and at about 08:00, the CO_2 concentration exceeded 1500 ppm. After that, CO_2 concentrations were almost all above 1000 ppm during periods of classroom occupancy. The variation of CO_2 concentrations in the three study classrooms on each day was similar, increasing at times the classroom was occupied and decreasing at times when the pupils were taking a break. The magnitude of the increase and decrease was mainly related to the number of pupils in the classroom and the times when windows were opened. The CO_2 concentration decreased after school was over until the time that the classrooms were closed to the CO_2 concentration outside. The rate of decline depended mostly on whether the windows were opened or not after school was over. During the occupied period, the variation of temperature is also related to the frequency and length of window opening, which is very similar with CO_2 concentration. The range of indoor temperature variations in the three classrooms was 16.50–22.23 °C in S1, 16.75–22.73 °C in S2 and 18.77–22.29 °C in N1, respectively, which indicates that the indoor temperature fluctuates slightly.



(**a**)



(**b**)



(**c**)

Figure 5. CO_2 concentration and temperature values in S1(**a**), S2(**b**) and N1(**c**) between the 7th and the 11th of March 2016 (the shadowed areas correspond to the occupied periods).

4.1.1. IAQ Evaluation by CO_2 Concentration

The maximum, minimum and average daily CO_2 concentrations in the three study classrooms are shown in Table 5. The variation range of the daily average CO_2 concentration of the three classrooms during the occupied period was between 1510 ppm and 3863 ppm. The highest daily average was about 4 times the recommended value. In the periods of I-T, there was no significant difference in the frequency of window openings between S1 and S2, while the window opening frequency in

N1 was significantly lower than that of S1 and S2. The weekly average CO_2 concentration of N1 was significantly higher than that of S2 and S1 during the occupied period, while the frequency of window opening in N1 is lowest among the three classrooms. The larger the maximum value of CO_2 concentration, the smaller the room ventilation rate, and small ventilation rates caused the CO_2 concentration to steadily increase. The daily maximum CO_2 concentration of the three classrooms occurred during the occupied periods. The maximum CO_2 concentration value of N1 occurred on Monday and Tuesday, and it exceeded 5000 ppm (the maximum limit that can be measured by the instrument). The maximum CO_2 concentration of S1 was 4982 ppm, which occurred on Tuesday, and the maximum CO_2 concentration of S2 was 3736 ppm, which occurred on Friday; both of these values are far greater than the reference maximum value of 1,080 ppm. The minimum CO_2 concentration values of the three classrooms ranged from 374 to 549 ppm, which are relatively close to the outdoor concentration, and all of these occurred during unoccupied periods. The average CO_2 concentration from 06:50 to 07:00 was calculated, and its variation range was 376 to 628 ppm. The CO_2 concentration level at this time can be regarded as the ideal initial value of the occupied period.

Table 5. Indoor CO_2 concentration (ppm) in the three study classrooms.

Classroom	Value	Period	Monday	Tuesday	Wednesday	Thursday	Friday
S1	Max.	Measurement *	3771	4982	3181	3079	2581
	Min.	Measurement *	451	400	374	429	549
	Avg. ±SD	Occupied	1849 ± 736	3023 ± 1068	1582 ± 571	1590 ± 505	1510 ± 479
		Unoccupied	1009 ± 274	654 ± 249	449 ± 47	623 ± 177	783 ± 220
		6:50–7:00	451 **	484 ± 8	444 ± 15	450 ± 14	573 ± 11
S2	Max.	Measurement *	3596	3718	3228	3539	3736
	Min.	Measurement *	459	523	454	459	453
	Avg. ±SD	Occupied	2015 ± 656	2426 ± 900	1850 ± 691	1843 ± 652	1916 ± 654
		Unoccupied	638 ± 162	859 ± 393	829 ± 381	601 ± 149	729 ± 261
		6:50–7:00	459 **	566 ± 4	476 ± 8	472 ± 14	472 ± 17
N1	Max.	Measurement *	5000	5000	3306	3568	3133
	Min.	Measurement *	476	455	421	374	398
	Avg. ±SD	Occupied	3863 ± 1013	3556 ± 1220	2421 ± 579	2526 ± 686	2448 ± 585
		Unoccupied	1535 ± 932	799 ± 527	599 ± 298	743 ± 539	750 ± 574
		6:50–7:00	476 **	628 ± 1	487 ± 6	376 ± 2	487 ± 6

Note: * For both occupation and unoccupied periods. ** Value recorded at 07:00 on Monday.

During the periods of C-T, pupils' brains must be engaged, and their behavior is strictly controlled. It is more important to ensure the air quality during periods of C-T than at other times. According to the National Standard [44], the recommended ventilation rate for pupils is not less than 20 m^3/s per person (circa 5.556 l/s per person). The air exchange rates required in the three study classrooms were 4.532/h in classroom S1, 3.838/h in S2 and 4.430/h in N1. The ventilation rate and air exchange rate in the three classrooms were calculated by measuring the CO_2 concentration at the beginning and end of each C-T period using formula (1) (3). The maximum, minimum and average values of ventilation rates and air exchange rates during C-T time periods are shown in Table 6.

Table 6. Ventilation rates and air exchange rate (AER) in C-T.

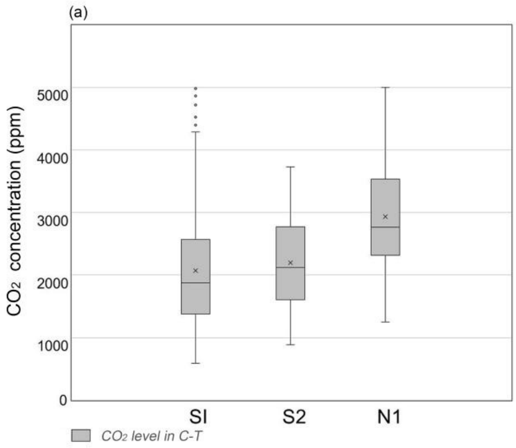
Classroom	Ventilation Rate (L/s per Person)			Recommended Value (L/s per Person)	Air exchange Rate (h^{-1})			Recommended Value (h^{-1})
	Min	Max	Avg.±SD		Min	Max	Avg.±SD	
S1	0.163	4.255	1.925±1.42	5.556	0.133	4.403	1.5705±1.15	4.532
S2	0.014	5.798	1.741±1.52	5.556	0.010	4.006	1.2035±1.05	3.838
N1	0.365	2.441	1.291±0.52	5.556	0.283	1.889	0.9995±0.40	4.430

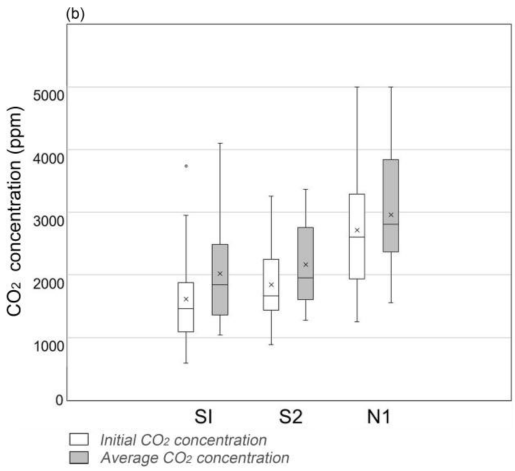
The ventilation rates of each C-T period in the three classrooms ranged from 1.291 to 1.925 L/s per person, which is much lower than the recommended value of 5.56 L/s per person. About 99%

of ventilation rates of the C-T periods in three classrooms were lower than the recommended value, except that the ventilation rate of the fourth class period in Classroom S2 reached 5.79 L/s per person on Wednesday. 84.6% of the ventilation rates were less than half the recommended value, and 34.6% of the ventilation rates were less than 1 L/s per person.

Corresponding to the ventilation rates, 97.4% of the air exchange rates were much lower than required, and 70% of the air exchange rates were less than 1.5/h. The air exchange rates in the N1 classroom were the lowest, with 90% of them being less than 1.5/h.

The serious insufficiency of ventilation caused excessive CO_2 concentrations. Figure 6a shows the level of CO_2 in the three study classrooms during the C-T periods. The CO_2 concentration ranged from 696 to 4982 ppm in S1; from 884 to 3736 ppm in S2; and from 1254 to 5000 ppm in N1. CO_2 concentration in all three classrooms was always at a high level, with median values of 2093 ppm (S1), 1875 ppm (S2) and 2766 ppm (N1). The percentages of measured CO_2 values that exceeded 1080 ppm were 93.94% (S1), 99.05% (S2) and 100% (N1); those exceeding 2500 ppm were 50% (S1), 48% (S2) and 60% (N1).





(**a**) (**b**)

Figure 6. CO_2 concentration distributions: (**a**) initial CO_2 concentration and (**b**) average CO_2 concentration.

During the C-T periods, the CO_2 concentration in the three study classrooms generally showed an upward trend. Statistical results indicate that the higher the initial value of CO_2 concentration in the classrooms, the higher the average value (see Figure 6b). The initial CO_2 concentration of 94.3% in the three classrooms was higher than 1000 ppm; these values were 696–3420 ppm (S1); 957–3514 ppm (S2); and 1452–5000 ppm (N1). The maximum values of the average CO_2 concentration in the three study classrooms were 3384 ppm (S1), 4229 ppm (S2) and 5000 ppm (N1); these values are 3–5 times the reference value. The mean median CO_2 concentration values were 1843 ppm (S1), 1955 ppm (S2) and 2808 ppm (N1).

We sought to further analyze the speed by which classroom CO_2 concentration exceeded the standard during the C-T periods, and to determine the effect of window opening on reducing CO_2 concentrations during the I-T periods. According to Equation (4), the variation rates of CO_2 concentration in the three classrooms were calculated. The fastest variation rate and corresponding CO_2 values, ventilation rates and air exchange rates are shown in Table 7. During the C-T periods, the fastest rate of increase in the CO_2 concentration was 46.3 ppm/min in S1, meaning that CO_2 concentration increased by 1621 ppm in 35 minutes. The corresponding ventilation rate and air exchange rate were only 0.439 L/s per person and 0.358/h, respectively. The corresponding values for classroom S2 were 44.5 ppm/min, 0.556 L/s per person and 0.431/h; for classroom N1, they were 35.8 ppm/min, 0.556 L/s per person and 0.431/h. These results are also related to the initial CO_2 concentration. Given the same difference, the lower the initial concentration, the larger the ventilation rate. The rising rate of CO_2 indicates that ventilation was necessary during the C-T periods, because CO_2 increased by 700 ppm in the three classrooms within 20 minutes under closed conditions.

Table 7. The fastest rate of variation in CO_2 concentrations and corresponding parameters.

Period	Room	Time * (min)	Variation Rate ** (ppm/min)	CO_2 Concentration (ppm) Initial	End	Diff. ***	Ventilation Rate (L/s per Person)	Air Exchange Rate (h^{-1})
C-T	S1	35	46.3	669	2290	1621	0.439	0.358
	S2	40	44.5	1788	3569	1781	0.014	0.010
	N1	40	35.8	1643	3076	1433	0.556	0.431
I-T	S1	S	−123.9	4982	3743	−1239	2.307	1.881
		L	−53.9	3618	1460	−2158	2.044	1.646
	S2	S	−98.5	3492	2507	−985	2.799	2.283
		L	−52.6	3736	1631	−2105	1.814	1.480
	N1	S	−29.7	2987	2690	−297	0.890	0.726
		L	−52.7	3437	1328	−2109	1.076	0.878

* Dring the I-T periods: S = short intervals, L = short intervals; ** The fastest rate of increase during C-T periods and the fastest rate of decline during I-T periods; *** Diff. = difference value between the initial value and ending value of each C-T and I-T period.

Class breaks proved to be good times for ventilation. In this study, most of the I-T period CO_2 concentrations showed decreases. The decline rates of CO_2 concentration affected the initial concentration of the next C-T period. The faster the CO_2 decline rate, the larger the decline range in a limited time, and the closer the CO_2 concentration came to the ideal initial value. Table 7 shows the maximum decline rate of CO_2 concentration in short and long periods of I-T. Assuming that the classroom was empty during the I-T period, the ventilation and air exchange rates were calculated according to equations (2) and (3).

The maximum decline rate of CO_2 concentration in S1 and S2 during the I-T periods was 2–3 times that of the increase rate during the C-T periods. The corresponding ventilation rates in S1 and S2 were 2.307 L/s per person and 2.799 L/s per person, respectively. The fastest decline rate of CO_2 concentration in the N1 classroom in a short I-T period was only 29.7 ppm/min, and the corresponding ventilation rate was only 0.890 L/s per person. The fastest CO_2 concentration declining rates of the three classrooms during the long I-T period were similar, ranging from 52.6 ppm/min to 53.9 ppm/min; this was slightly higher than the fastest increase rate during the C-T periods. However, the corresponding ventilation rates were 2.004 L/s per person in S1, 1.814 L/s per person in S2 and 1.076 L/s per person in N1. The ventilation volume for all intervals was less than the standard value. The same as [27], although CO_2 concentration of S1 was reduced by as much as 1239 ppm in 10 minutes, it was still insufficient to maintain acceptable level. According to previous statistics, 97.3% of the initial concentration during the C-T periods exceeded 1000 ppm, indicating that there was not enough ventilation during the I-T periods to reduce the CO_2 concentration to a level that was close to that of the outdoor value.

It can be seen from the above that the IAQ of the three classrooms is very poor due to the serious insufficiency of ventilation. Opening windows during the I-T period can effectively reduce the initial value of CO_2 in the next C-T. However, the air quality in the C-T period cannot be guaranteed only by after-class ventilation.

4.2. Questionnaire Surveys

4.2.1. Satisfaction Evaluation and Air Freshness Perception of IAQ

The voting results of the perception of air freshness are shown in Figure 7. The voting results of pupils in the three classrooms were very similar. Most of the pupils felt that the air was fresh. The voting rates for feeling fresh air (A) were 68.4% in S1, 71.9% in S2 and 69.4% in N1. The votes for sensing non-fresh air (B) were 10.5% in S1, 12.5% in S2 and 8.3% in N1. The number of responders who chose option C (non-fresh or smelly air) in S1 and N1 were twice that of those who chose option B. Pupils in classroom S2 chose option B as well as option C. No one thought that the classroom smelled bad for a long period of time, except for one boy in S2.

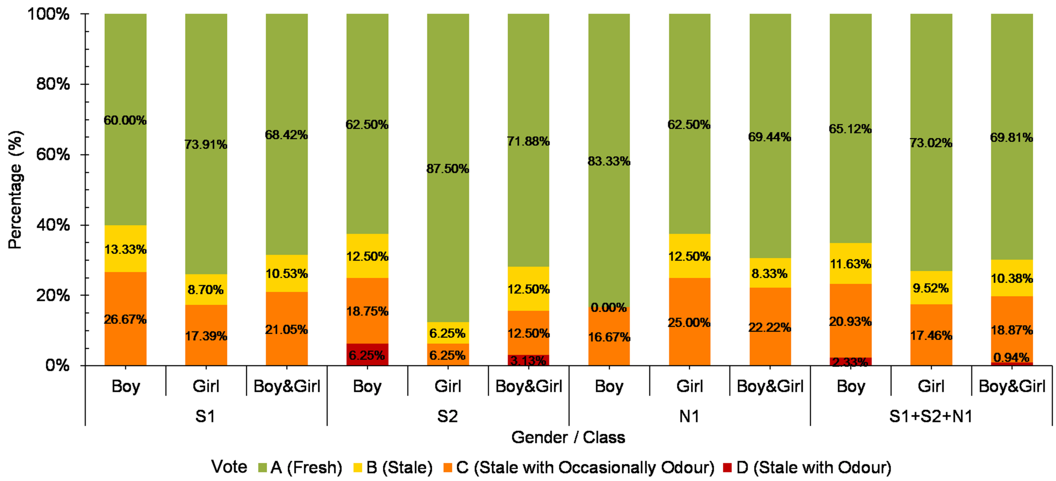


Figure 7. The air freshness votes in the three study classrooms.

The votes of boys and girls in each class were compared. There were few differences in voting between boys and girls in the same classroom. 87.5% of girls and 56.3% of boys in classroom S2 voted that they felt the air was fresh. However, it can be seen that overall, 62.5% of girls and 83.3% of boys in classroom N1 thought that the indoor air was fresh in their classrooms. The difference in voting between boys and girls in S1 was significantly smaller than that in S2 and N1. Overall, there was no significant difference between genders by comparing the votes of boys and girls in three classrooms.

Usually, classroom odors come from children's metabolism and breathing, which can accumulate during prolonged presence in an enclosed space. Although most pupils have a sensitive sense of smell, they remain in classrooms for a long period of time and have a certain degree of adaptability to and tolerance of their environment [46]. During the survey period, the average CO_2 concentration values during the third class period in the three study classrooms were about twice the standard value: 1802 ppm in S1, 1705 ppm in S2 and 2450 ppm in N1. Nearly 70% of the pupils still thought the air was fresh, indicating their adaptability to the air environment. Pupils' votes that the air was fresh were not affected by different levels of CO_2 concentration.

The voting results of satisfaction with the indoor air quality of the three classrooms are shown in Table 8 and Figure 8. 80.2% of pupils expressed their satisfaction with IAQ (A+B). 84.2% of S1 pupils, 77.5% of S2 pupils and 69.5% of N1 pupils cast satisfied votes. At the same time, only 2.6% to 6.2% of all pupils in the three classrooms voted that they found the IAQ unsatisfactory (D+E). The average level of unsatisfactory votes was only 3.7%, indicating that most pupils were satisfied with the indoor air quality. Although the satisfaction rate of the N1 classroom was lower than that of the S1 and S2 classrooms, the unsatisfactory votes of N1 was only 2.1%, slightly less than that of the other two classrooms. Fewer boys in the three classrooms voted that the air quality was good (A+B) than girls did, but the difference was not significant between genders.

Table 8. S1, S2 and N1 satisfied (with the air quality) votes.

Vote of Pupils	Very Satisfied	Satisfied	Neutral	Dissatisfied	Very Dissatisfied
	(A)	(B)	(C)	(D)	(E)
S1	44.7%	39.5%	13.2%	2.6%	0.0%
S2	50.0%	37.5%	6.3%	3.1%	3.1%
N1	52.8%	16.7%	27.8%	2.1%	0.0%
S1+S2+N1	49.1%	31.1%	16.1%	2.8%	0.9%

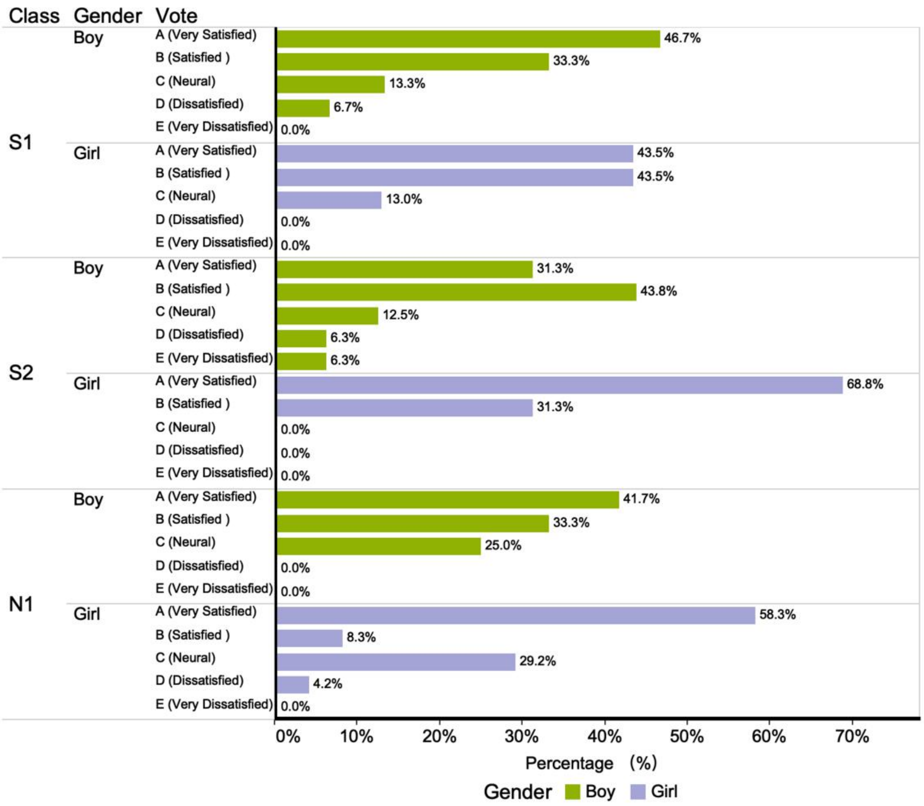


Figure 8. The satisfied votes of boys and girls in the three classrooms.

The overall comparison of the votes of boys and girls showed no significant difference, which indicats that gender did not affect the evaluation results. Compared with the votes regarding air freshness, the voting trend of satisfaction with air quality in the three classrooms was consistent with that of perception of air freshness. 30.2% of the pupils (B+C+D) voted that the air was not fresh, and 19.8% of the pupils (C+D) voted that it was smelly. These feelings did not reflect the votes on IAQ satisfaction. This indicates that pupils considered the air quality to be acceptable or satisfactory, even though they felt that the air was not fresh. The average CO_2 concentration was 100% over the standard value, but the unsatisfactory vote percentage (3.7%) was significantly different from the actual situation, indicating that the actual CO_2 concentrations did not affect pupils' satisfaction with air quality. This also shows that most pupils did not notice or mind air quality problems caused by excessive CO_2. High CO_2 concentration did not bring obvious bad mood to most children. Pupils' positive evaluation of the IAQ may affect their willingness to open windows (i.e., they most often would not open them), resulting in a low frequency of window openings.

4.2.2. The Purpose and Willingness to Open Windows

Generally, the purpose of window ventilation is to reduce indoor temperatures [27,47] or improve indoor air quality [36]. The results of the present study are that most pupils opened windows to improve indoor air quality rather than to reduce the classroom temperature. Statistical results show that 82.1% of pupils in the three classrooms opened windows for ventilation to improve air quality, 12.2% to cool the classroom temperature, and 5.7% for other reasons.

Figure 9 shows pupils' votes on their perception and satisfaction with indoor temperatures. 75.5% of the pupils thought the temperature was suitable, 12.3% thought the temperature was low, 11.3% thought it was warm, and 0.9% thought it was hot. 86.8% of the pupils (A+B) were satisfied with the indoor temperature, while only 5.6% of the pupils (D+E) were not satisfied. The results of pupils' voting on temperature perception and satisfaction re-validate the purpose of pupils' window opening; i.e., most pupils open windows to improve air quality even at comfortable temperatures.

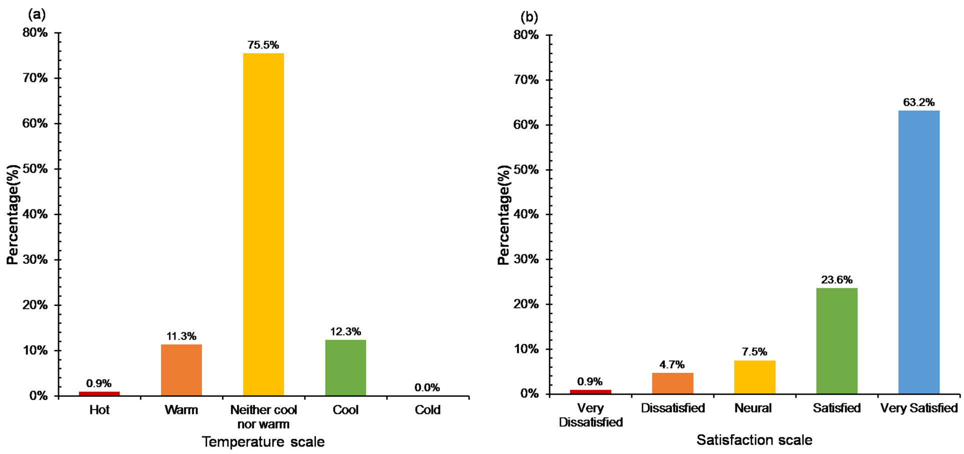


Figure 9. Pupils' perception (**a**) and satisfaction (**b**) with classroom temperature.

In this paper, the results of voting on pupils' comfort level with opening windows are shown in Table 9 and Figure 10. Voting showed that 87.7% of the pupils in the three classrooms (A+B+C) did not feel uncomfortable, despite the open windows allowing cold air to enter the classroom. This indicates that the majority of the pupils accepted the practice of window opening. 55% of the pupils voted that they felt comfortable (voting A+B) opening windows for ventilation, indicating that most pupils tended to open windows. Comparing the votes among the pupils in the three classrooms, it was found that the proportion of pupils feeling comfortable with opening windows (voting A+B) was 76.3% in the three classrooms. The proportion of pupils feeling uncomfortable (voting D+E) was only 5.3%. Although the frequency of window opening in classroom S2 was higher than that in N1, pupils in S2 and N1 voted more consistently on their attitude toward window opening, and the proportion of those feeling comfortable (voting A+B) was 53.1% and 50.3%, respectively. The voting rates of feeling uncomfortable (voting D+E) in S2 and N1 were 15.6% and 16.7%, respectively, which were significantly higher than that in S1. No effect of gender was found on the perception of window opening. The proportion of boys and girls who felt comfortable (voting A+B) was 60%. The proportion of girls who felt uncomfortable (voting D+E) was 14.3%, slightly higher than that of boys (9.3%).

Table 9. S1, S2 and N1 window opening comfort votes.

Classroom	Very Comfortable	ComfortableNeutral		Uncomfortable	Very Uncomfortable
	(A)	(B)	(C)	(D)	(E)
S1	31.6%	44.7%	18.4%	5.3%	0.0%
S2	25.0%	28.1%	31.3%	15.6%	0.0%
N1	30.6%	19.4%	33.3%	13.9%	2.8%
S1+S2+N1	29.3%	31.1%	27.4%	11.3%	0.9%

Most pupils accepted the window opening behavior, which should be helpful for improving indoor air quality. However, the actual ventilation rate was very low (calculated in Section 4.1.2). No relationship was found between the observed frequency of, and comfort with, opening windows. Pupils in the three classrooms almost never opened windows in the C-T periods, and the frequency of window openings in S1 and S2 was significantly higher than in N1 during the I-T periods. Consistent with the frequency of window openings, the votes for comfort with window opening in S1 were significantly higher than those in classroom N1. However, the statistical results did not show a difference between S2 and N1 in terms of votes for comfort with window opening.

Research shows that the two main purposes of window opening are to reduce temperature or to improve indoor air quality; these purposes may be affected by subjective feelings. First, most pupils in this study thought that the indoor temperature was appropriate. Few pupils thought that the indoor temperature was high, and they lacked the subjective will to open windows to cool down. Second, most of the pupils in this study thought that the indoor air quality was good and very satisfactory. This may be the reason for not opening windows, because pupils did not think it necessary to open windows to improve IAQ.

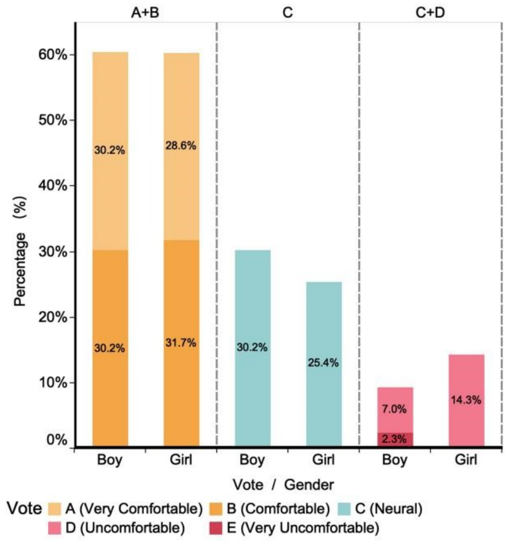


Figure 10. Votes regarding pupils' comfort level with opening windows.

5. Conclusions

During the heating season in severe cold weather areas of China, CO_2 concentrations in three classrooms of a naturally ventilated primary school in Shenyang, located in northeast China, were continuously measured for one week. Meanwhile, 106 pupils were asked to complete subjective questionnaires on air quality.

The results show that the daily average concentration of CO_2 in the three classrooms in the occupied periods varied from 1500 to 3863 ppm, which is far beyond the standard value of 1000 ppm, and the CO_2 concentrations during the Class-Time periods were higher than during other periods. The main reason for the excessive CO_2 concentrations in the classrooms was that the ventilation rate was insufficient due to the low frequency of window opening. About 99% of the ventilation rates during the Class-Time periods were lower than the recommended value. According to the calculated increase rate of carbon dioxide in the three study classrooms, the carbon dioxide level in closed classrooms could exceed 700 ppm in 20 minutes, which indicates that it is necessary to increase the ventilation rates during the Class–Time periods. In parallel, although the indoor carbon dioxide concentration can be reduced by 1230 ppm in 10 minutes by opening windows during the Intermittent–Time periods, 97% of the initial CO_2 concentrations in the Class-Time periods were more than 1000 ppm, indicating that the ventilation rate was also insufficient in the interval times.

Through the statistical voting results of the pupils' subjective evaluations (questionnaires), it was found that there was no significant difference in the voting proportion among classrooms or between genders. Although the levels of CO_2 in all three classrooms exceeded the recommended values during the questionnaire period, 69.8% of the pupils voted that they found the air in their classrooms to be fresh, which is inconsistent with the actual CO_2 measurement results. Most pupils opened windows to improve indoor air quality. However, only 3.7% of the pupils were not satisfied with the air quality, which greatly reduced their willingness to open windows and hindered the behavior of opening windows. Increasing the frequency of window opening would increase the ventilation rate, if the pupils had higher acceptance of window opening.

In summary, no relationship was found between the measured CO_2 concentrations and the pupils' perception of the freshness of the air. There was a significant difference between high indoor

CO_2 concentrations and air quality satisfaction voting, which is a reminder that window opening frequency should be controlled according to ventilation requirements, rather than by occupants' subjective judgment.

Author Contributions: Conceptualization, F.M. and C.Z.; methodology, F.M.; software, X.X.; validation, F.M., C.Z. and X.X.; formal analysis, F.M.; investigation, F.M. and X.X.; resources, F.M.; data curation, F.M. and X.X.; writing—original draft preparation, F.M.; writing—review and editing, F.M. and C.Z.; visualization, F.M. and X.X.; supervision, C.Z.; project administration, F.M. and C.Z.; funding acquisition, F.M.

Funding: This research was funded by Liaoning Science and Technology Project, grant number: 2017231009.

Acknowledgments: The authors greatly appreciate the financial support by the Liaoning Science and Technology Project (Grant no. 2017231009). Assistance provided by the measurement school' pupils and teachers are also gratefully acknowledged.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Fisk, W.J. The ventilation problem in schools: Literature review. *Indoor Air* **2017**, *27*, 1039–1051. [CrossRef]
2. Faustman, E.M.; Faustman, E.M.; Silbernagel, S.M.; Fenske, R.A.; Burbacher, T.M.; Ponce, R.A. Mechanisms underlying Children's susceptibility to environmental toxicants. *Environ Health Perspect.* **2000**, *108*, 13–21. [PubMed]
3. Suk, W.A.; Murray, K.; Avakian, M.D. Environmental hazards to children's health in the modern world. *Mutat. Res. Rev. Mutat. Res.* **2003**, *544*, 235–242. [CrossRef]
4. Branco, P.T.B.S.; Alvim-Ferraz, M.C.M.; Martins, F.G.; Sousa, S.I.V. Children's exposure to indoor air in urban nurseries-part I: CO_2 and comfort assessment. *Environ. Res.* **2015**, *140*, 1–9. [CrossRef] [PubMed]
5. GB50099-2011. *Code for Design of School*; China Architecture & Building Press: Beijing, China, 2010.
6. Dorizas, P.V.; Assimakopoulos, M.N.; Helmis, C.; Santamouris, M. An integrated evaluation study of the ventilation rate, the exposure and the indoor air quality in naturally ventilated classrooms in the Mediterranean region during spring. *Sci. Total Environ.* **2015**, *502*, 557–570. [CrossRef] [PubMed]
7. Bakó-Biró, Z.; Clements-Croome, D.J.; Kochhar, N.; Awbi, H.B.; Williams, M.J. Ventilation rates in schools and pupils' performance. *Build. Environ.* **2012**, *48*, 215–223. [CrossRef]
8. Schibuola, L.; Scarpa, M.; Tambani, C. Natural ventilation level assessment in a school building by CO_2 concentration measures. *Energy Procedia* **2016**, *101*, 257–264. [CrossRef]
9. Behzadi, N.; Fadeyi, M.O. A preliminary study of indoor air quality conditions in Dubai public elementary schools. *Archit. Eng. Des. Manag.* **2012**, *8*, 192–213. [CrossRef]
10. Becker, R.; Goldberger, I.; Paciuk, M. Improving energy performance of school buildings while ensuring indoor air quality ventilation. *Build. Environ.* **2007**, *42*, 3261–3276. [CrossRef]
11. Shendell, D.G.; Prill, R.; Fisk, W.J.; Apte, M.G.; Blake, D.; Faulkner, D. Associations between classroom CO_2 concentrations and student attendance in Washington and Idaho. *Indoor Air* **2004**, *14*, 333–341. [CrossRef]
12. Gaihre, S.; Semple, S.; Miller, J.; Fielding, S.; Turner, S. Classroom carbon dioxide concentration, school attendance, and educational attainment. *J. Sch. Health* **2014**, *84*, 569–574. [CrossRef]
13. Haverinen-Shaughnessy, U.; Moschandreas, D.J.; Shaughnessy, R.J. Association between substandard classroom ventilation rates and students' academic achievement. *Indoor Air* **2011**, *21*, 121–131. [CrossRef] [PubMed]
14. 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. [CrossRef]
15. Wargocki, P.; Wyon, D.P. The effects of moderately raised classroom temperatures and classroom ventilation rate on the performance of schoolwork by children (RP-1257). *HVAC&R Res.* **2007**, *13*, 193–220.
16. Coley, D.A.; Greeves, R.; Saxby, B.K. The effect of low ventilation rates on the cognitive function of a primary school class. *Int. J. Vent.* **2007**, *6*, 107–112. [CrossRef]
17. Wargocki, P.; Wyon, D.P. Effects of HVAC on student performance. *ASHRAE J.* **2006**, *48*, 22.
18. Fadeyi, M.O.; Alkhaja, K.; Sulayem, M.B.; Abu-Hijleh, B. Evaluation of indoor environmental quality conditions in elementary schools' classrooms in the United Arab Emirates. *Front. Archit. Res.* **2014**, *3*, 166–177. [CrossRef]

19. Godwin, C.; Batterman, S. Indoor air quality in Michigan schools. *Indoor Air* **2007**, *17*, 109–121. [CrossRef] [PubMed]
20. Stabile, L.; Dell'Isola, 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. [CrossRef]
21. Turanjanin, V.; Vučićević, B.; Jovanović, M.; Mirkov, N.; Lazović, I. Indoor CO_2 measurements in Serbian schools and ventilation rate calculation. *Energy* **2014**, *77*, 290–296. [CrossRef]
22. Pereira, L.D.; Raimondo, D.; Corgnati, S.P.; da Silva, M.G. Assessment of indoor air quality and thermal comfort in Portuguese secondary classrooms: Methodology and results. *Build. Environ.* **2014**, *81*, 69–80. [CrossRef]
23. Twardella, D.; Matzen, W.; Lahrz, T.; Burghardt, R.; Spegel, H.; Hendrowarsito, L.; Frenzel, A.C.; Fromme, H. Effect of classroom air quality on students' concentration: Results of a cluster-randomized cross-over experimental study. *Indoor Air* **2012**, *22*, 378–387. [CrossRef]
24. Cornaro, C.; Paravicini, A.; Cimini, A. Monitoring indoor carbon dioxide concentration and effectiveness of natural trickle ventilation in a middle school in Rome. *Indoor Built Environ.* **2013**, *22*, 445–455. [CrossRef]
25. Jones, B.; Kirby, R. Indoor air quality in U.K. school classrooms ventilated by natural ventilation windcatchers. *Int. J. Vent.* **2012**, *10*, 323–337. [CrossRef]
26. Coley, D.A.; Beisteiner, A. Carbon dioxide levels and ventilation rates in schools. *Int. J. Vent.* **2002**, *1*, 45–52. [CrossRef]
27. Griffiths, M.; Eftekhari, M. Control of CO_2 in a naturally ventilated classroom. *Energy Build.* **2008**, *40*, 556–560. [CrossRef]
28. Stazi, F.; Naspi, F.; Ulpiani, G.; Di Perna, C. Indoor air quality and thermal comfort optimization in classrooms developing an automatic system for windows opening and closing. *Energy Build.* **2017**, *139*, 732–746. [CrossRef]
29. American Society of Heating, Refrigerating and A-C Engineers Fdn. *ASHRAE Standard 62.1-2016 Ventilation for Acceptable Indoor Air Quality*; American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc.: Atlanta, GA, USA, 2016.
30. Satish, U.; Mendell, M.J.; Shekhar, K.; Hotchi, T.; Sullivan, D.; Streufert, S.; Fisk, W.J. Is CO_2 an indoor pollutant? Direct effects of low-to-moderate CO_2 concentrations on human decision-making performance. *Environ. Health Perspect.* **2012**, *120*, 1671–1677. [CrossRef]
31. Muscatiello, N.; McCarthy, A.; Kielb, C.; Hsu, W.H.; Hwang, S.A.; Lin, S. Classroom conditions and CO_2 concentrations and teacher health symptom reporting in 10 New York State schools. *Indoor Air* **2015**, *25*, 157–167. [CrossRef]
32. Toftum, J.; Kjeldsen, B.U.; Wargocki, P.; Menå, H.R.; Hansen, E.M.; Clausen, G. Association between classroom ventilation mode and learning outcome in Danish schools. *Build. Environ.* **2015**, *92*, 494–503. [CrossRef]
33. Heudorf, U. Passive-house schools—A tool for improving indoor air quality in schools. *Gesundheitswesen (Bundesverband Arzte Offentlichen Gesundheitsdienstes (Germany))* **2007**, *69*, 408–414. [CrossRef]
34. Wargocki, P.; Wyon, D.P. 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**, *13*, 165–191.
35. Canha, N.; Mandin, C.; Ramalho, O.; Wyart, G.; Ribéron, J.; Dassonville, C.; Hänninen, O.; Almeida, S.M.; Derbez, M. Assessment of ventilation and indoor air pollutants in nursery and elementary schools in France. *Indoor Air* **2016**, *26*, 350–365. [CrossRef] [PubMed]
36. Santamouris, M.; Synnefa, A.; Asssimakopoulos, M.; Livada, I.; Pavlou, K.; Papaglastra, M.; Gaitani, N.; Kolokotsa, D.; Assimakopoulos, V. Experimental investigation of the air flow and indoor carbon dioxide concentration in classrooms with intermittent natural ventilation. *Energy Build.* **2008**, *40*, 1833–1843. [CrossRef]
37. Mumovic, D.; Palmer, J.; Davies, M.; Orme, M.; Ridley, I.; Oreszczyn, T.; Judd, C.; Critchlow, R.; Medina, H.A.; Pilmoor, G.; et al. Winter indoor air quality, thermal comfort and acoustic performance of newly built secondary schools in England. *Build. Environ.* **2009**, *44*, 1466–1477. [CrossRef]
38. Teli, D.; James, P.A.B.; Jentsch, M.F. Thermal comfort in naturally ventilated primary school classrooms. *Build. Res. Inf.* **2013**, *41*, 301–316. [CrossRef]
39. Chen, L.; Fang, X.Q.; Li, S.; Zhang, S.F. Comparisons of energy consumption between cold regions in China and the Europe and America. *J. Nat. Resour.* **2011**, *26*, 1258–1268.

40. Peng, Z.; Deng, W.; Tenorio, R. Investigation of indoor air quality and the identification of influential factors at primary schools in the North of China. *Sustainability* **2017**, *9*, 1180. [CrossRef]
41. Wang, D.; Jiang, J.; Liu, Y.; Wang, Y.; Xu, Y.; Liu, J. Student responses to classroom thermal environments in rural primary and secondary schools in winter. *Build. Environ.* **2017**, *115*, 104–117. [CrossRef]
42. GB/05189-2015. *The Design Standard for Energy Efficiency of Public Buildings*; China Architecture & Building Press: Beijing, China, 2015.
43. Wargocki, P.; Da Silva, N.A.F. Use of visual CO_2 feedback as a retrofit solution for improving classroom air quality. *Indoor Air* **2015**, *25*, 105–114. [CrossRef] [PubMed]
44. GB/T17226-2017. *Hygienic Requirements of Classroom Ventilation in Middle and Elementary School*; Standards Press of China: Beijing, China, 2017.
45. Persily, A.; de Jonge, L. Carbon dioxide generation rates for building occupants. *Indoor Air* **2017**, *27*, 868–879. [CrossRef]
46. Chen, W. *Research on Indoor Air Quality of University Classroom in Northern Area in China, in Thermal Power Engineering*; Harbin Engineering University: Harbin, China, 2007.
47. Perna, C.D.; Mengaroni, E.; Fuselli, L.; Stazi, A. Ventilation strategies in school buildings for optimization of air quality, energy consumption and environmental comfort in Mediterranean climates. *Int. J. Vent.* **2011**, *10*, 61–78. [CrossRef]