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Effects of COVID-19 pandemic control and prevention measures

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Ventilation and thermal conditions in secondary schools in the Netherlands: Effects of COVID-19 pandemic control and prevention measures

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ABSTRACT

During the COVID-19 pandemic, the importance of ventilation was widely stressed and new protocols of ventilation were implemented in school buildings worldwide. In the Netherlands, schools were recommended to keep the windows and doors open, and after a national lockdown more stringent measures such as reduction of occupancy were introduced. In this study, the actual effects of such measures on ventilation and thermal conditions were investigated in 31 classrooms of 11 Dutch secondary schools, by monitoring the indoor and outdoor CO_2 concentration and air temperature, both before and after the lockdown. Ventilation rates were calculated using the steady-state method. Pre-lockdown, with an average occupancy of 17 students, in 42% of the classrooms the CO_2 concentration exceeded the upper limit of the Dutch national guidelines (800 ppm above outdoors), while 13% had a ventilation rate per person (VR_p) lower than the minimum requirement (6 l/s/p). Post-lockdown, the indoor CO_2 concentration decreased significantly while for ventilation rates significant increase was only found in VR_p, mainly caused by the decrease in occupancy (average 10 students). The total ventilation rate per classrooms, mainly induced by opening windows and doors, did not change significantly. Meanwhile, according to the Dutch national guidelines, thermal conditions in the classrooms were not satisfying, both pre- and post-lockdown. While opening windows and doors cannot achieve the required indoor environmental quality at all times, reducing occupancy might not be feasible for immediate implementation. Hence, more controllable and flexible ways for improving indoor air quality and thermal comfort in classrooms are needed.

1. Introduction

In the beginning of 2020, the COVID-19 pandemic aroused worldwide concern about indoor air quality (IAQ) and ventilation, especially in indoor environments with a high occupancy, such as educational buildings. “Proper” ventilation was proposed as a measure to reduce the possible airborne transmission of SARS-CoV-2 [1]. Determining how much ventilation is required and how the indoor space is ventilated are particularly important for school classrooms, because of their dense occupancies of students and a possibly higher risk of airborne transmission [2]. However, in previous studies it has already been observed that school classrooms are often poorly ventilated [3,4], and it became a very urgent problem to be further investigated in light of the ongoing pandemic.

In many countries, schools were closed during the periods of national COVID-19 lockdowns [5,6]. In the Netherlands, the first so-called “intelligent” lockdown started on March 15, 2020, and lasted until June 1, 2020. Then, on October 14, 2020, a “partly” lockdown began, which turned into the first lockdown on December 15, 2020 and lasted until March 1, 2021. During the “partly” lockdown, the pandemic control and prevention measures implemented in schools included opening the windows and doors for a lack of mechanical ventilation systems, and from December 1, 2020, wearing face masks became mandatory inside the school buildings, but not necessary during the lessons. During the first lockdown, schools were mostly closed (only used for exams and students with special needs). After the first lockdown, additional

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measures were introduced in schools: 1.5 m distance between students, and half occupancy of the classes (e.g., utilizing different school buildings, adjusting classroom floor areas, and alternating online/offline groups). Since June 2021 schools were fully reopened, yet soon later at the end of the summer of 2021 the COVID-19 cases increased, and measures were again introduced. From December 19, 2021 to January 10, 2022, the second lockdown became a fact. Finally, on March 23, 2022 all measures were stopped. Throughout the entire period schools were recommended to open windows and doors in the school classrooms in the absence of a mechanical ventilation system [7].

Indoor environmental quality (IEQ) and ventilation in school classrooms have been a focus of research for many years. Numerous studies all over the world have been performed to document the indoor environment in classrooms and to examine its relations with diseases, disorders and learning ability [8]. Several cross-sectional studies among European countries [9–12] have investigated IEQ and health of school children. In the US, several studies explored the relations between ventilation rates, attendance rates, and student performance (for example in Refs. [13–15]). Moreover, in a number of countries (such as Sweden [16], the Netherlands [17,18], the UK [19], Greece [20], Finland [21], Denmark [22], Portugal [23], Australia [24], Japan [25] and China [26]), health effects were assessed using self-administered questionnaires, combined with indoor environmental monitoring of several air pollutant concentrations as well as inspection of buildings with the use of a checklist and/or several physical measurements (e.g. temperature and relative humidity). The studies found several different shortcomings in the environmental conditions in classrooms, such as poor ventilation, noise, inadequate heating or lighting, already during non-pandemic periods.

To determine whether a space is ventilated properly, the indoor CO_2 concentration can be monitored and used as a proxy for ventilation performance [27]. To date, many studies have been conducted around the world to measure the CO_2 concentration in school classrooms and thus examine whether the ventilation performance fulfils the standards and guidelines [28–30]. A CO_2 concentration of 1000 ppm is often taken as the upper limit for a good IAQ according to the previous version of ASHRAE Standard 62.1, and has been also suggested as the upper limit for CO_2 monitoring to ensure sufficient ventilation in the REHVA COVID-19 Guidance, which is approximately equivalent to a ventilation rate of 10 l/s per person [31–33]. In the Netherlands, the Building Decree prescribes minimum ventilation rates expressed in l/s per person for educational buildings that existed before 2012 (3.4 l/s per person) and built after 2012 (8.5 l/s per person) [34]. Meanwhile, the Dutch Fresh Schools guidelines [35] - adapted from several commonly used international standards (e.g., EN 16798–1 [36] and ISO 7730 [37]) with more stringent requirements - has been enacted in particular for primary and secondary schools. In this guideline, the ventilation rate is suggested for three different levels: 12 l/s per person (level A, very good), 8.5 l/s per person (level B, good) and 6 l/s per person (level C, acceptable), for which the corresponding indoor CO_2 concentration is 400, 550, and 800 ppm above the outdoor level, respectively.

With the increased concern about the indoor environmental quality (IEQ) driven by the COVID-19 pandemic, researchers once again set off investigations among school classrooms within the past two year. In a study initiated by the Dutch National Ventilation Coordination Team (LCVS) before the second lockdown in which CO_2 monitors were placed in educational buildings, the results showed that only 38% of the tested schools (7340 elementary and secondary schools in the Netherlands) met the ventilation requirements of the Dutch Building Decree [38]. Furthermore, a third of the schools only had natural ventilation, where the fresh air supply in the classrooms was often inadequate. However, when keeping windows and doors opened became a major pandemic control and prevention protocol, especially for the naturally ventilated spaces, lower CO_2 concentrations and better ventilation have been observed among different types of educational buildings [39–41]. Nevertheless, in the meantime studies have also found that such measures for improving ventilation could cause negative impact on other aspects of IEQ for the students, such as thermal comfort and acoustics, according to both physical measurements and subjective assessments [42–44].

Ever since the "partly" lockdown took place, the same ventilation protocol of opening windows and doors has been implemented among the Dutch secondary schools. In addition, other measures such as reducing occupancy were also introduced after the first lockdown. What effects do these measures have on ventilation and the thermal conditions inside the classrooms are still unknown. Therefore, a field study was conducted among the secondary schools in the Netherlands to investigate 1) the ventilation sufficiency, 2) the ventilation-related effects of temporary school or governmental initiated pandemic control and prevention measures, and 3) the thermal conditions as a result of the implemented measures, in the classrooms under the COVID-19 pandemic.

2. Methods

2.1. Selection of schools and classrooms

Between October and December 2020, 20 secondary schools in different regions and cities of the Netherlands were enrolled on a voluntary basis, as reported in Ref. [45]. Among them, 11 schools which were visited both before and after the first lockdown (herein referred to as "the lockdown"), were included in this study (named from S1 to S11). The locations of the selected schools are shown in Fig. 1, where eight of them are located in an urban area, and the other three in a rural area. These 11 schools cover different types of secondary education in the Netherlands, namely pre-university education, general secondary education, and pre-vocational secondary education, with students generally aged between 12 and 18.

The basic information on the 11 schools is listed in Table 1. The first school visits were all conducted during the heating season (October 20 to December 15, 2020), while for the second school visits, nine (S1–S9) were conducted during the heating season (March 11 to April 23, 2021), and the other two (S10 and S11) during the non-heating season (May 10 and June 3, 2021). Among the 11 schools, nine (82%) of them have classrooms with only natural ventilation (openable windows and doors), three (27%) have classrooms equipped with mechanical air supply, two (18%) have classrooms equipped with mechanical air exhaust, and nine (82%) have classrooms equipped with both mechanical air supply and exhaust. Only two schools (6%), S7 and S11, have a centralized ventilation system, with all the classrooms having the same mechanical air supply and exhaust equipment.

In each school, two to four classrooms were selected, based on the type of ventilation regimes operated. For natural ventilation, one or two classrooms at different orientations or floor levels were selected, while for balanced mechanical ventilation and hybrid ventilation (with only mechanical air supply or mechanical air exhaust), only one classroom was selected. In total, 36 classrooms (named from C1 to C36) were selected to perform the comparison between pre- and post-lockdown periods, of which three (C10, C15, C24) were practical classrooms (with practical settings for preparatory vocational courses of housekeeping and metalworking, etc.), and the rest were theoretical classrooms (with normal classroom settings of desks and chairs). During the post-lockdown period, C12, C23, and C36 were not in use, for which a similar classroom was chosen, as C12′, C23′, and C36′, respectively. Meanwhile, C9 and C20 were used in combination with the adjacent classroom (doubled floor area and volume), and thus are marked as C9′ and C20'.

2.2. Survey

The survey of the schools consisted of monitoring of the indoor and outdoor CO_2 concentration and air temperature, an interview with the

Fig. 1. Location of the involved secondary schools in the Netherlands (adapted from Google Maps, 2022).

Table 1
Basic information on the selected schools.

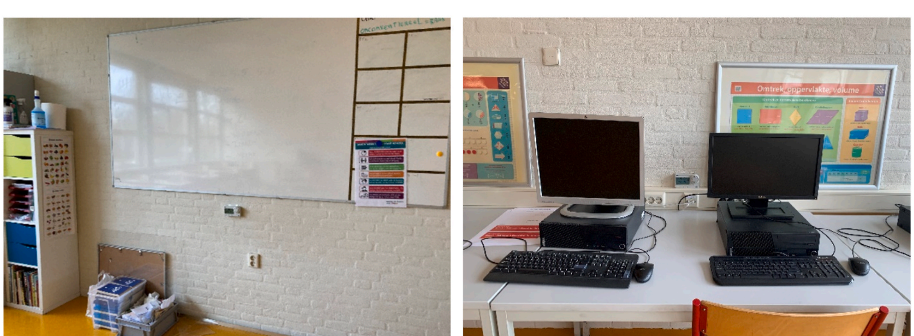
School	Date of 1st visit (pre-lockdown)	Date of 2nd visit (post-lockdown)	Location	Year of construction[a]	Ventilation regime[b]
S1	20/10/2020	08/04/2021	Haarlem (Urban)	1975/1992/2006	N, ME, MT
S2	21/10/2020	11/03/2021	Hilversum (Urban)	1952/2012	N, MS, MT
S3	27/10/2020	13/04/2021	IJsselstein (Urban)	1970	N, MT
S4	28/10/2020	25/03/2021	Breukelen (Rural)	1960/1999	N, MT
S5	06/11/2020	26/03/2021	Delft (Urban)	1999	N, MS
S6	12/11/2020	12/03/2021	Delft (Urban)	1965	N, MT
S7	16/11/2020	23/04/2021	Utrecht (Urban)	1978	N, MT
S8	26/11/2020	09/04/2021	Arnhem (Rural)	1983	N, MT
S9	03/12/2020	16/04/2021	IJmuiden (Rural)	1931	N, MT
S10	10/12/2020	10/05/2021	Amersfoort (Urban)	1960/1990/2013	N, ME, MS
S11	15/12/2020	03/06/2021	's-Hertogenbosch (Urban)	1953	N. MT

[a] Some schools have different buildings or different parts of the building complex that were built in different years.
[b] Ventilation regimes available in the school building(s). N: natural ventilation; MS: only mechanical air supply; ME: only mechanical air exhaust; MT: both mechanical air supply and exhaust.

facility manager, an inspection of the school buildings, HVAC (heating, ventilation and air conditioning) systems, and classrooms, and monitoring of the occupancy and occupants' behaviors. Each school visit started in the morning, and lasted for one school day.

2.2.1. Monitoring of CO_2 concentration and air temperature

The CO_2 concentration and air temperature were monitored indoors and outdoors, using HOBO® MX1102A loggers (CO_2 sensor: 0–5000 ppm/±50 ppm ± 5% of reading; temperature sensor: 0–50 °C/±0.21 °C). In order to obtain a more accurate result of the indoor CO_2 concentration, two sampling points were selected in each classroom, namely on both the front and back walls at the height of the breathing zone of the sitting students (approximately 1.1–1.3 m), where the devices were installed on the walls using adhesive tapes [46]. The CO_2 concentration and air temperature inside the classrooms were continuously monitored and recorded during the school hours, with a time



(a) (b)

Fig. 2. Examples of indoor CO_2 concentration and air temperature sampling points in the classrooms: (a) front wall; (b) back wall.

interval of 30 s. During the pre-lockdown period, the outdoor CO_2 concentration and air temperature were monitored at the entrance of the school building, both in the morning and in the afternoon, for 15 min. During the post-lockdown period, the outdoor CO_2 concentration and air temperature were monitored both at the entrance and in the courtyard (at least 5 m from the building façade in order to reduce the possible influence of indoor CO_2 concentration and human activities) of the school, for the whole school day. In Figs. 2 and 3 some examples of the location of the indoor and outdoor sampling points are presented, respectively.

2.2.2. Technical questionnaire and interview

Before each school visit, the school facility managers were asked to complete a technical questionnaire based on the characteristics of the school buildings, including the basic information on the building construction, the type of HVAC systems, and the maintenance of the facilities (Appendix A).

During each school visit, an inspection of the buildings and HVAC systems was made together with the facility manager(s). In addition, a short interview was conducted to ask the facility manager(s) about the COVID-19 measures implemented at the school, ventilation regimes used, occupancy, teaching schedule, and cleaning procedures (Appendix B).

2.2.3. Classroom checklist

The inspection of the selected classrooms was conducted based on a classroom checklist [18], which included items about indoor environmental settings, humidity problems, indoor climate characteristics, ventilation equipment, and indoor pollution sources (Appendix C). One checklist was completed for each classroom.

2.2.4. Monitoring of occupancy and ventilation-related behavior

The teachers giving lessons in the selected classrooms were asked to fill in an observation form for each lesson they taught, which included the time (duration) of the lesson, the number of students present, and their behaviors related to ventilation during the lesson (e.g., opening/closing windows/doors) (Appendix D). Such observations were also performed by the researchers once per lesson per classroom (Appendix D).

2.3. Ethical aspects

After the recruitment of the schools, the director of the school received a letter with a detailed procedure of the intended monitoring, measurements and observations, as well as the promise that no pictures with children would be made. For ethical approval there was a waiver from the ethics committee of the University of Utrecht, because it did not fall under the Act Research with Human Subjects.

2.4. Data analysis

2.4.1. Data cleaning

First, the measurement data of CO_2 and air temperature was extracted from the HOBOs and imported to IBM SPSS Statistics 26.0 (SPSS Inc. Chicago, IL, USA). Then the imported data was screened based on Z-scores, where all the data points with a Z-score (absolute value) higher than three were eliminated as outliers [47]. The information collected through the technical questionnaires, inspections, interviews, classroom checklists, and observational forms were manually screened and typed in IBM SPSS Statistics 26.0. All the subsequent statistical analyses were also performed with IBM SPSS Statistics 26.0.

It needs to be noted that for the data analyses, C7, C9 (C9′), C20 (C20'), C30 were excluded because they only had one occupied lesson during at least one of the school visits. C31 was excluded because the indoor CO_2 concentration was most of the time lower than the average outdoor level during the second school visit, which was considered a measurement error. Therefore, the results presented in this paper include 31 classrooms.

2.4.2. Time distribution of indoor CO_2 concentration and air temperature

Since the Dutch Fresh Schools guidelines [35] is mostly implemented for school buildings in the Netherlands, it is taken as the major reference for assessing ventilation and thermal conditions of the classrooms in this study. Accordingly, the indoor CO_2 concentration as an indicator of ventilation sufficiency is assessed based on three threshold levels, namely from low to high: level A (Very good), level B (Good), and level C (Acceptable), of which the indoor CO_2 concentration is less than 400 ppm, 550 ppm, and 800 ppm above the outdoor level, respectively. In other words, indoor CO_2 concentration exceeding level C is considered as not acceptable. Therefore, the indoor CO_2 concentration can be sorted into four categories, namely ≤ level A, > level A - ≤ level B, > level B - ≤ level C, and > level C. In this study, the outdoor CO_2 concentration for each school was represented by the average value of the outdoor data collected during each visit. The time distribution of indoor CO_2 concentration among the four categories during the total occupied time (excluding breaks and unoccupied lessons (number of students = 0)) was calculated for each classroom.

Similarly, three ranges of indoor air temperature (min - max) are also prescribed in the Fresh School 2021 guidelines, namely from narrow to wide: range A (Very good), range B (Good), and range C (Acceptable) [35]. The ranges applicable to the heating and non-heating season are different. For heating season the ranges are set as fixed values, where range A = 20–23 °C, range B = 19–24 °C, and range C = 18–25 °C. For non-heating season, the ranges are calculated based on equations (1)–(3) [35]:

For range A:

$$T_{in} = 0.33T_{RMOT} + 16.4 \pm 2\,^{\circ}C \quad (1)$$

(a) (b)

Fig. 3. Examples of outdoor CO_2 concentration and air temperature sampling points at the schools: (a) entrance; (b) courtyard.

For range B:

$$T_{in} = 0.33T_{RMOT} + 16.4 \ \pm 3\,^{\circ}C \tag{2}$$

For range C:

$$T_{in} = 0.33T_{RMOT} + 16.4 \ \pm 4\,^{\circ}C \tag{3}$$

where:

- T_{in} is the required indoor air temperature
- T_{RMOT} is the running mean outdoor air temperature (RMOT). In this study, due to the limitation of measurements, it is simplified as the average of all outdoor data collected during each school visit.

Although the ranges of required indoor air temperature changes with the outdoor air temperature during the non-heating season, a fixed upper limit is set at 25.5 °C, 26 °C, and 27 °C for range A, B, and C, respectively.

Accordingly, the indoor air temperature can be sorted into seven categories, namely $< C_{min}$, $\geq C_{min}$ - $< B_{min}$, $\geq B_{min}$ - $< A_{min}$, $\geq A_{min}$ - $\leq A_{max}$, $> A_{max}$ - $\leq B_{max}$, $> B_{max}$ - $\leq C_{max}$, and $> C_{max}$, where indoor air temperature lower than C_{min} or higher than C_{max} is considered as not acceptable. The time distribution of indoor air temperature among the seven categories during the total occupied time was then calculated for each classroom.

2.4.3. Ventilation rate

The ventilation rate in the classrooms was calculated using the steady-state method, based on the CO_2 concentrations monitored [48]. Based on a prior study [46], for every occupied lesson in the surveyed classrooms, a 5-min period was selected for the calculation, during which time the CO_2 concentration was relatively steady. It was assumed that no factors other than the occupancy and ventilation settings were affecting the CO_2 concentration in the classrooms, and thus the steady-state condition of the selected periods was verified using one-way ANOVA. The average CO_2 concentration among all the sampling points in one classroom during the 5-min period was determined as the steady-state CO_2 concentration. The ventilation rate (VR) per occupied lesson was then calculated according to equation (4) [48,49]:

$$VR = \frac{10^6 n G_p}{C_{steady} - C_{out}} \tag{4}$$

where:

- n is the average number of students in the classroom during the lesson
- G_p is the average CO_2 generation rate per person, which is estimated as 0.0045 l/s per person (16 l/h per person) for both students (12–18 years old) and teachers (30–40 years old) [50]
- C_{steady} is the steady-state CO_2 concentration (ppm)
- C_{out} is the outdoor CO_2 concentration (ppm), which is calculated as presented in section 2.4.2 for each school

The ventilation rate (l/s) of each occupied lesson was then divided by the number of students and the floor area of the classroom, respectively, to calculate the ventilation rate per person (VR_p) (l/s/p) and per m^2 floor area (VR_a) (l/s/m^2).

2.4.4. Statistical analysis

The indoor CO_2 concentration and air temperature during the occupied lessons were compared between the pre- and post-lockdown periods using Mann-Whitney *U*-tests for each individual classroom. The percentages of time of 1) CO_2 concentration above the threshold level A, B, and C, 2) air temperature outside range A, B, and C, were compared between the pre- and post-lockdown periods using Wilcoxon signed-rank tests at classroom level. The ventilation rates were compared between the pre- and post-lockdown periods using Wilcoxon signed-rank tests also at classroom level. The outdoor CO_2 concentration and air temperature were compared between the pre- and post-lockdown periods using Wilcoxon signed-rank tests at school level. The significance level was set at 0.05 ($P < 0.05$).

As the ventilation rates should be regarded as clustered by repeated measurements (school visits and occupied lessons) for each classroom, generalized estimating equations (GEE) analysis with linear function was used to study the association between VR_p and 1) student occupancy, 2) number of opened windows, 3) number of opened doors, and 4) pre- and post-lockdown visits [51,52]. Both the univariable analysis of each of the factors and the mutually adjusted multivariable analysis of all the factors were conducted. VR_p was chosen as the main dependent variable of the GEE model because it is the main parameter assessed in relevant standards and guidelines. Accordingly, the subject variable is "classroom ID", and the within-subject variables are "visit" (pre- and post-lockdown) and "lesson" (occupied lessons). An independent correlation matrix was introduced to the model. The mutually adjusted multivariable regression model can be written as equation (5) [51–53]:

$$E(Y) = \beta_0 + \beta_1 occupancy + \beta_2 window + \beta_3 door + \beta_4 visit \tag{5}$$

where:

- Y is the natural logarithm of VR_P per lesson of each classroom (ln VR_P). The data of VR_P was transformed because its distribution was right-skewed. In the results, exponentiated beta's are reported for VR_P.
- β_1 is the main effect of occupancy
- *occupancy* is the number of students per lesson of each classroom
- β_2 is the main effect of opening window(s)
- *window* is the number of opened windows per lesson of each classroom
- β_3 is the main effect of opening door(s) compared to door(s) closed
- $door = 1$ if the door was opened, 0 if the door was closed, during each lesson of each classroom
- β_4 is the main effect of visit
- $visit = 1$ if before lockdown, 2 if after lockdown

3. Results

3.1. Overview of classrooms

The characteristics of the studied classrooms are listed in Table 2. Among these 31 classrooms, 15 (48%) only use natural ventilation, three (10%) have mechanical air supply, three (10%) have mechanical air exhaust, and 10 (32%) have both mechanical air supply and exhaust. All the classrooms have openable windows, where most of them are top-hung or side-hung windows, and can be opened up to an angle of 30°–45°. During the time when the survey was conducted, windows and doors were often kept opened during the occupied lessons in order to increase outdoor air supply and improve ventilation in the classrooms, as one of the COVID-19 pandemic control and prevention measures. Therefore, natural ventilation should also be considered in use inside many of the classrooms that have mechanical ventilation. The passive grilles available in the classrooms can also contribute to natural ventilation. For the mechanically ventilated classrooms, the air inlets and outlets are all located on the ceiling. With regards to heating, C7, C14, and C20 have floor heating, C35 and C36 have heated air supply, while all the other classrooms have hot water radiators.

3.2. CO_2 concentrations

3.2.1. Indoor and outdoor CO_2 concentrations before and after lockdown

The indoor and outdoor CO_2 concentrations of the classrooms both before and after the lockdown during the occupied lessons are presented

Table 2
Characteristics of the 31 classrooms.

School	Classroom[a,b]	Floor area (m^2)	Volume (m^3)	Ventilation regime available[c]	Presence of passive grilles[d]	Location of air inlet[e]	Location of air outlet[f]	Heating[g]
S1	C1	43	151	N	No	–	–	R
	C2	47	122	ME + N	No	–	Ceiling	R
	C3	62	186	MT + N	No	Ceiling	Ceiling	R
S2	C4	55	149	MT + N	No	Ceiling	Ceiling	R
	C5	53	148	N	Yes	–	–	R
	C6	53	148	N	Yes	–	–	R
S3	C8	55	165	N	No	–	–	R
	C10	88	264	N	Yes	–	–	R
S4	C11	59	142	N	No	–	–	R
	C12 (12′)	59 (59)	189 (189)	N	No	–	–	R
	C13	64	198	MT + N	No	Ceiling	Ceiling	R
S5	C14	56	280	MS + N	Yes	Ceiling	–	F
	C15	308	893	MS + N	Yes	Ceiling	–	R
	C16	55	187	N	Yes	–	–	R
	C17	84	294	N	Yes	–	–	R
S6	C18	50	150	N	Yes	–	–	R
	C19	46	138	N	Yes	–	–	R
	C21	53	164	N	Yes	–	–	R
S7	C22	67	201	MT + N	No	Ceiling	Ceiling	R
	C23 (23′)	56 (61)	168 (183)	MT + N	No	Ceiling	Ceiling	R
	C24	215	645	MT + N	No	Ceiling	Ceiling	R
S8	C25	52	156	N	Yes	–	–	R
	C26	53	159	MT + N	Yes	Ceiling	Ceiling	R
	C27	53	159	N	Yes	–	–	R
S9	C28	58	174	N	No	–	–	R
	C29	74	259	MT + N	No	Ceiling	Ceiling	R
S10	C32	48	163	ME + N	No	–	Ceiling	R
	C33	51	163	MS + N	No	Ceiling	–	R
	C34	100	280	ME + N	Yes	–	Ceiling	R
S11	C35	71	227	MT + N	No	Ceiling	Ceiling	A
	C36 (36′)	54 (54)	173 (173)	MT + N	No	Ceiling	Ceiling	A

[a] The numbers in the parentheses are the information on the substituting classrooms in the post-pandemic school visit.
[b] C7, C9 (C9′), C20 (C20′), C30, and C31 were excluded from the data analyses due to lack of data or invalid measurements.
[c] Ventilation regime(s) available in the classroom. N: natural ventilation; MS: only mechanical air supply; ME: only mechanical air exhaust; MT: both mechanical air supply and exhaust.
[d] All the passive ventilation grilles are located on the window(s).
[e] Location of the air inlet of the mechanical ventilation system.
[f] Location of the air outlet of the mechanical ventilation system.
[g] R: hot water radiator; F: floor heating; A: heated air supply.

in Fig. 4. The indoor CO_2 concentration varied a lot among the classrooms. Before the lockdown, the mean CO_2 concentration in the classrooms ranged from 458 to 1255 ppm, with an average of 825 ppm. The peak CO_2 concentration ranged from 515 to 2604 ppm, with an average of 1254 ppm. Besides, the mean difference of indoor and outdoor CO_2 concentration ranged from 35 to 1084 ppm, with an average of 371 ppm. After the lockdown, the mean CO_2 concentration in the classrooms ranged from 459 to 941 ppm, with an average of 654 ppm. The peak CO_2 concentration ranged from 507 to 1885 ppm, with an average of 903 ppm. The mean difference of indoor and outdoor CO_2 concentration ranged from 4 to 488 ppm, with an average of 216 ppm. For the comparison between pre- and post-lockdown periods, the P-values of the Mann-Whitney *U*-tests are marked in Fig. 4 for the classrooms. In 24 (77%) of the 31 classrooms the indoor CO_2 concentration during the pre-lockdown period was significantly higher than the post-lockdown period, while in five (16%) classrooms the indoor CO_2 concentration was significantly lower during the pre-lockdown period than the post-lockdown period. In the other two classrooms, the indoor CO_2 concentration showed no significant difference between the pre- and post-lockdown periods.

In addition, the outdoor CO_2 concentration varied considerably, with both time and location. Before the lockdown, the mean outdoor CO_2 concentration ranged from 261 to 450 ppm among the 11 schools, with an average of 371 ppm, while after the lockdown it ranged from 292 to 462 ppm, with an average of 426 ppm. According to the Wilcoxon signed-rank tests, the outdoor CO_2 concentrations were significantly higher during the post-lockdown period than during the pre-lockdown period ($P = 0.026$) (Table 3). Interestingly, the schools with a lower outdoor CO_2 concentration are not necessarily located in the rural area, and vice versa. For instance, before the lockdown, S6 and S9 had an average outdoor CO_2 concentration lower than 300 ppm, while after the lockdown it increased above 450 ppm at both locations.

3.2.2. *Time distribution of indoor CO_2 concentrations*

The percentages of time when the CO_2 concentration inside the classrooms fell into the four categories of the Dutch Fresh Schools guidelines are presented in Fig. 5. During the pre-lockdown period, on the one hand 13 (42%) of the 31 classrooms had the CO_2 concentration sometimes above level C, with C4 being the highest (65% of time > level C). On the other hand, 18 (58%) classrooms had the CO_2 concentration always (100% of the time) below level C, and nine (25%) and six (17%) classrooms always below level B and A, respectively. During the post-lockdown period, the number of classrooms having CO_2 concentration sometimes above level C decreased to 3 (8%), with C12 being the highest (18% of time > level C). Moreover, the number of classrooms that had CO_2 concentration always below level C, B, and A had increased to 28 (90%), 21 (68%) and 13 (42%), respectively. On average, before the lockdown in 52%, 32% and 12% of the occupied time the indoor CO_2 concentration was above level A, B, and C, respectively, while after the lockdown the percentages of time decreased to 14%, 5%, and 1%, respectively.

According to the Wilcoxon signed-rank tests (Table 3), the percentages of time when the indoor CO_2 concentration exceeded level A, B, and C were significantly higher during the pre-lockdown period than that

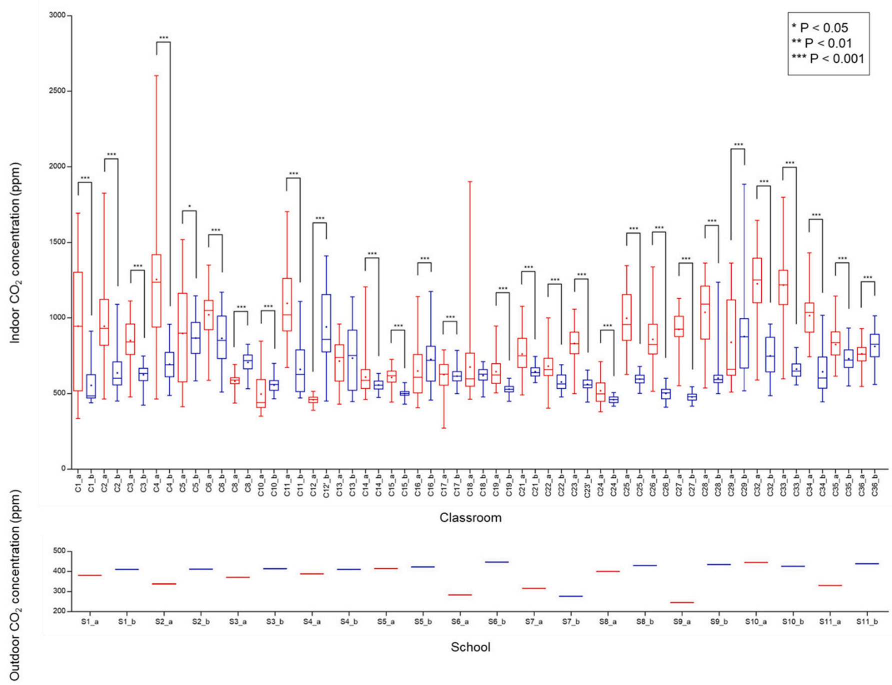


Fig. 4. Indoor and outdoor CO_2 concentrations (a: pre-lockdown period; b: post-lockdown period). Above: box and whiskers plot of indoor CO_2 concentration inside the classrooms (P: Mann-Whitney *U*-tests between pre- and post-lockdown period); Below: average outdoor CO_2 concentration at each school.

during the post-lockdown period, where for both level A and B, $P < 0.001$, and for level C, $P = 0.003$.

3.3. Ventilation rates

The numbers of opened windows and doors, number of students, and calculated ventilation rates of the classrooms during the occupied lessons before and after the lockdown are presented in Table 4. During the pre-lockdown period, the mean VR ranged from 66.6 l/s (C28) to 1931.9 l/s (C10) among the classrooms, with an average of 270.2 l/s. The mean VR_p ranged from 4.6 l/s/p (C1) to 241.5 l/s/p (C10), with an average of 21.8 l/s/p. The mean VR_a ranged from 0.9 l/s/m^2 (C28) to 12.8 l/s/m^2 (C12), with an average of 3.5 l/s/m^2.

During the post-lockdown period, the mean VR ranged from 71.0 l/s (C32) to 1116.7 l/s (C27), with an average of 271.3 l/s. The mean VR_p ranged from 7.4 l/s/p (C13) to 155.8 l/s/p (C27), with an average of 32.5 l/s/p. The mean VR_a ranged from 1.0 l/s/m^2 (C24) to 25.3 l/s/m^2 (C20), with an average of 4.9 l/s/m^2. According to the results of the Wilcoxon signed-rank tests (Table 3), for VR, $P = 0.302$, for VR_p, $P = 0.005$, and for VR_a, $P = 0.251$.

The number of students during the occupied lessons ranged from 7 (C36) to 29 (C19), with an average of 17. The number of students during the occupied lessons ranged from 5 (C32) to 21 (C12' and C13), with an average of 10. Except for a decrease in occupancy in most of the classrooms, it maintained the same in three (10%) classrooms, and increased in one (3%) classroom. Overall, the numbers of students were significantly higher during the pre-lockdown period than those of the post-lockdown period according to the Wilcoxon signed-rank tests (Table 3), where $P < 0.001$.

Moreover, during the pre-lockdown period, 28 (90%) of the 31 classrooms had at least one window continuously opened during the occupied lessons, and 18 (58%) had the door opened, while during the post-lockdown period 24 (77%) classrooms had at least one window continuously opened during the occupied lessons, and 20 (65%) had the door opened.

The results of the GEE analysis are listed in Table 5. VR_p was significantly associated with the student occupancy in the classrooms ($P < 0.001$) and the visit ($P < 0.001$) according to the univariable analysis. The difference in VR_p between pre- and post-lockdown visits was no longer significant after adjusting for student occupancy and opening of doors and windows, suggesting that the difference between pre- and post-lockdown visits was mainly due to the change in occupancy. Besides, the numbers of opened windows and doors were not significantly associated to VR_p according to both the univariable and multivariable analyses. The association between VR_p and student occupancy remained significant after adjustment, with an estimated exponentiated β of 0.938 (95% CI: 0.915–0.963), meaning on average VR_p is multiplied by 0.938 per one student occupancy increase in the classrooms.

3.4. Temperatures

3.4.1. Indoor and outdoor air temperatures before and after lockdown

The indoor and outdoor air temperatures of the classrooms both before and after the lockdown during the occupied lessons are shown in Fig. 6. Similar to the CO_2 concentration, the indoor air temperature in the classrooms varied considerably. Before the lockdown, the mean air temperature in the classrooms ranged from 17.3 °C (C8) to 23.9 °C (C17), with an average of 20.4 °C. The lowest and highest air temperature measured in the classrooms was 16.1 °C (C8) and 24.8 °C (C17), respectively. Besides, the mean indoor-outdoor temperature differences ranged from 1.6 (C24) to 11.4 °C (C34), with an average of 6.6 °C. After the lockdown, the average air temperature in the classrooms ranged from 17.8 °C (C1) to 24.4 °C (C36), with an average of 20.9 °C. The lowest and highest air temperature measured in the classrooms was 15.4 °C (C4) and 27.1 °C (C22), respectively. The mean indoor-outdoor temperature differences ranged from −3.5 (C36) to 12.5 °C (C7), with an average of 6.2 °C. Three classrooms had indoor air temperature lower than the outdoor level, of which two (C8 and C10) were visited in the heating season (April 2021), and one (C36) in the non-heating season (June 2021).

For the comparison between pre- and post-lockdown periods, the P-values of the Mann-Whitney *U*-tests are marked in Fig. 6 for the classrooms. In 19 (61%) classrooms, the indoor air temperature during the pre-lockdown period was significantly lower than the post-lockdown

Table 3
Comparison of different parameters of CO_2 concertation, occupancy, ventilation rate, and air temperature in 31 classrooms (11 schools) between pre- and post-lockdown period.

Parameter	Pre-lockdown	Post-lockdown	P[a]
CO_2			
	Mean (Min-Max)[b]	Mean (Min-Max)	
Outdoor (ppm)	371 (261-450)	426 (292-462)	**0.026**
Indoor (ppm)	825 (458-1255)	654 (459-941)	**< 0.001**
Indoor - outdoor (ppm)	470 (35-1084)	216 (4-488)	**< 0.001**
Mean % of time > level A	52	14	**< 0.001**
% classrooms all time < level A	16	42	
Mean % of time > level B	32	5	**< 0.001**
% classrooms all time < level B	23	68	
Mean % of time > level C	12	1	**0.003**
% classrooms all time < level C	58	90	
Occupancy			
	Mean (Min-Max)	Mean (Min-Max)	
# of students in the classroom	17 (7-29)	10 (5-21)	**< 0.001**
Ventilation rate			
	Mean (Min-Max)	Mean (Min-Max)	
VR (l/s)	270.2 (66.6-1931.9)	271.3 (71.0-1116.7)	0.302
VRa (l/s/m²)	3.5 (0.9-12.8)	4.6 (1.0-21.1)	0.251
VR_p (l/s/p)	21.8 (4.6-241.5)	32.5 (7.4-155.8)	**0.005**
% classrooms with mean VR_p < 6 l/s/p (level C)	13	0	
% classrooms with mean VR_p < 8.5 l/s/p (level B)[c]	45	6	
% classrooms with mean VR_p < 10 l/s/p[d]	45	6	
% classrooms with mean VR_p < 12 l/s/p (level A)	65	13	
Temperature			
	Mean (Min-Max)	Mean (Min-Max)	
Outdoor (°C)	13.7 (8.6-17.4)	15.5 (8.8-27.5)	**0.021**
Indoor (°C)	20.4 (17.3-23.9)	20.9 (17.8-24.4)	0.092
Indoor - outdoor (°C)	6.6 (1.6-11.4)	6.2 (-3.5-12.5)	0.784
Mean % of time outside range A	50	34	0.052
% classrooms all time inside range A	6	16	
Mean % of time outside range B	22	15	0.140
% classrooms all time inside range B	45	45	
Mean % of time outside range C	10	6	0.794
% classrooms all time inside range C	68	58	

[a] Wilcoxon signed-rank test for two groups of 11 schools (outdoor) or 31 classrooms (indoor). Bold values denote P < 0.05.
[b] Mean, Min, and Max value of the means per school (outdoor) or per classroom (indoor).
[c] 8.5 l/s/p is also the minimum ventilation rate required by the Dutch Building Decree [34].
[d] 10 l/s/p is suggested by different standards and guidelines [33].

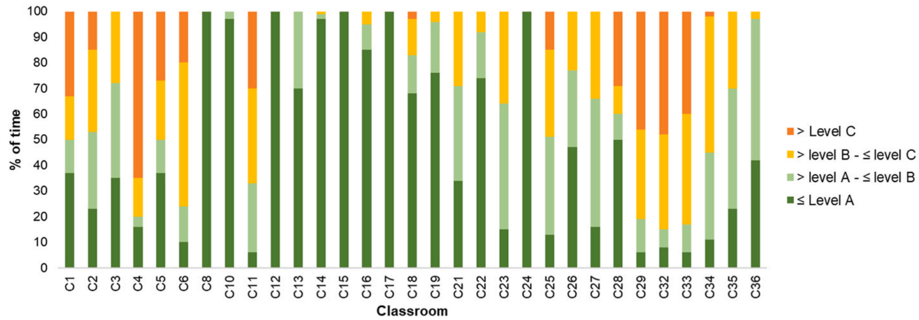
period, while in the other 12 (39%) classrooms the indoor air temperature was significantly higher during the pre-lockdown period than the post-lockdown period.

The outdoor air temperature also varied a lot throughout the two school visits. Before the lockdown, the mean outdoor air temperature ranged from 8.6 to 17.4 °C among the 11 schools, with an average of 13.7 °C, while after the lockdown it ranged from 8.8 to 27.5 °C, with an average of 15.5 °C. According to the Wilcoxon signed-rank tests (Table 3), the outdoor air temperatures were significantly higher during the post-lockdown period than during the pre-lockdown period ($P = 0.021$).

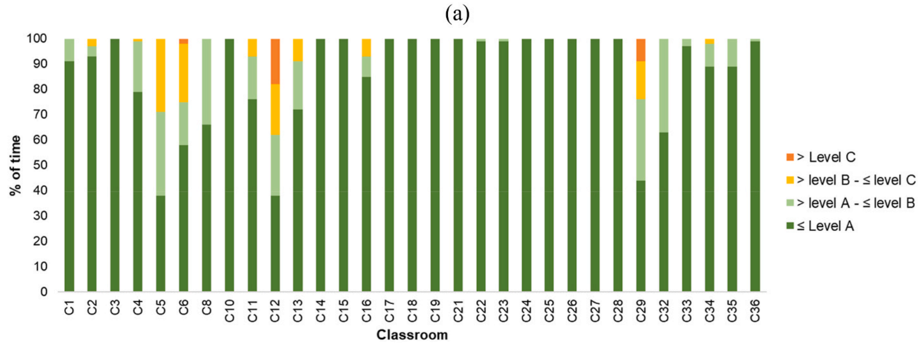
3.4.2. *Time distribution of indoor air temperatures*

The percentages of time when the air temperature inside the classrooms fell into the seven ranges of the Dutch Fresh Schools guidelines are presented in Fig. 7. During the pre-lockdown period, the air temperature in 25 (81%) classrooms was sometimes lower than A_{min}, while in 10 (32%) classrooms the air temperature was sometimes even lower than C_{min}, with C8 being the coldest (96% of time < C_{min}). Still, 68%, 45%, and 6% of the classrooms had the air temperature always within range C, B, and A, respectively. During the post-lockdown period, on the one hand, the air temperature was still sometimes lower than A_{min} in 23 (74%) classrooms, and 11 (35%) of them had the air temperature lower than C_{min}. While on the other hand, with the outdoor temperature increased with the seasons, more classrooms had the air temperature exceeded the upper limit of the threshold ranges, particularly in those visited during the non-heating season, where three (10%) of them had the air temperature sometimes higher than C_{max}.

On average, before the lockdown in 50%, 22%, and 10% of the occupied time the indoor air temperature fell outside range A, B, and C, respectively, while after the lockdown the percentages of time decreased to 34%, 15%, and 6%, respectively. However, according to the Wilcoxon signed-rank tests (Table 3), no significant difference was found in the mean percentages of time between the pre- and post-lockdown periods, with P-values of 0.052, 0.140, and 0.794, for ranges A, B, and C, respectively.



(a)



(b)

Fig. 5. Time distribution of CO_2 concentration during occupied lessons in the classrooms among different categories of Dutch Fresh Schools guidelines: (a) pre-lockdown; (b) post-lockdown.

4. Discussion

4.1. CO_2 concentrations and ventilation rates in school classrooms

During the pre-lockdown period, the outdoor CO_2 concentration varied considerably among the schools, with an average of 371 ppm and a range of 261–450 ppm. The classrooms were used with normal occupancy (7–29 students, mean 17 students) and with windows and doors opened. The average indoor CO_2 concentration spanned a range (458–1255 ppm) similar to several recent field studies [39,43,54], but lower than those measured in studies conducted during the previously non-pandemic era (600–2500 ppm) [4].

The indoor CO_2 concentration in the classrooms was on average more than 50% of the occupied time higher than level A of the Dutch Fresh Schools guidelines (400 ppm above outdoor level), which is the warning level suggested by the REHVA COVID-19 Guidance [32]. Also, on average over 30% of the time the indoor CO_2 concentration was higher than level B (550 ppm above outdoor level), which is approximately equal to the widely accepted threshold level of 1000 ppm [33]. Moreover, for an average of 12% of the time the indoor CO_2 concentration was higher than level C (800 ppm above outdoor level), which is the upper limit and considered not acceptable. In fact, 58% of the classrooms were able to keep the indoor CO_2 concentration all time below level C, while only one sixth of them had it always below level A, indicating periods of insufficient ventilation occurred in many classrooms even with windows and doors opened.

Before the lockdown, the average VR_p in the classrooms (4.6–64.1 l/s/p) was higher than the results reported in a number of recent studies (0.8–12.0 l/s/p) [54–56], yet for 13%, 45%, and 65% of the classrooms the average VR_p did not fulfill the level C, B, and A of the Dutch Fresh Schools guidelines, respectively. It should be noted that level B corresponds with the minimum requirement of the Dutch Building Decree (8.5 l/s/p) (Table 3). Furthermore, according to a number of studies and guidelines [33,57], a minimum ventilation rate of 10 l/s/p is recommended for a good indoor air quality. In the present study, however, 45% of the classrooms had an average VR_p lower than 10 l/s/p (Table 3).

Compared to the pre-lockdown period, the post-lockdown outdoor CO_2 concentration among the schools was significantly higher, with an average of 426 ppm and a range of 292–462 ppm. The number of occupants in the classrooms was significantly decreased (5–21 students, mean 10 students) in order to keep 1.5 m distance between the students. While not much changes were observed in the operation of windows and doors, a significant decrease was found in both the indoor CO_2 concentration (459–941 ppm) and the percentage of time the indoor CO_2 concentration was above level A (14%), B (5%), and C (1%), respectively (Table 3).

While no significant difference was found in both VR and VR_a, VR_p increased significantly after the lockdown (from an average of 15.3 l/s/p to 32.5 l/s/p). After the lockdown, VR_p in all the classrooms fulfilled the minimum requirement of the Dutch Fresh Schools guidelines (level C), 94% fulfilled the requirement of the Dutch Building Decree (level B), and 87% fulfilled level A (Table 3). Moreover, 94% of the classrooms had a VR_p higher than the recommended 10 l/s/p. Such results, however, were mostly due to the decrease in student occupancy, which was confirmed by the GEE analysis as only the occupancy showed a significant effect on VR_p (Table 5). In other words, the significant increase in VR_p during the post-lockdown period compared to the pre-lockdown period resulted mainly from the reduction in occupancy, and was not dependent on the operation of windows and doors.

4.2. Thermal conditions in school classrooms

Before the lockdown, all the school visits were conducted during the heating season. The outdoor air temperature varied with 8.8 °C and had an average of 13.7 °C. The indoor air temperature in the classrooms ranged from 17.3 to 23.9 °C, which was cooler than those measured in the schools located in the same climate zone during the heating season before the COVID-19 pandemic (19.0–26.0 °C) [18,58,59]. As shown in Fig. 7(a), according to the Dutch Fresh Schools guidelines, more than 80% of the classrooms had an indoor air temperature lower than the "very good" range (range A), while over 30% of them had an indoor air temperature lower than range C. In fact, on average, during 50% of the

Table 4
Ventilation rates, number of students, and number of opened windows and doors in the classrooms before and after the lockdown.

School	Classroom	Pre-lockdown (Mean (SD))[a]						Post-lockdown (Mean (SD))					
		Number of opened windows	Number of opened doors	Number of students	VR (l/s)	VR_p (l/s/p)	VR_a (l/s/m^2)	Number of opened windows	Number of opened doors	Number of students	VR (l/s)	VR_p (l/s/p)	VR_a (l/s/m^2)
S1	C1	1 (0)	0 (1)	21 (4)	95.8 (22.4)	4.6 (0.5)	2.2 (0.5)	1 (1)	1 (1)	10 (1)	418.0 (432.3)	41.3 (43.9)	9.7 (10.1)
	C2	4 (0)	1 (1)	17 (6)	167.8 (20.7)	10.9 (5.7)	3.6 (0.5)	2 (3)	1 (1)	9 (5)	118.6 (39.6)	17.7 (13.5)	2.5 (0.8)
	C3	0 (0)	0 (0)	18 (5)	176.2 (26.4)	10.7 (4.7)	2.8 (0.4)	0 (0)	0 (0)	14 (2)	283.5 (72.0)	19.9 (4.0)	4.6 (1.2)
S2	C4	1 (0)	0 (1)	15 (10)	82.9 (22.2)	7.8 (5.2)	1.5 (0.4)	2 (1)	1 (0)	11 (4)	221.7 (165.2)	18.2 (9.2)	4.0 (3.0)
	C5	2 (0)	1 (1)	24 (1)	211.4 (227.6)	8.4 (8.6)	4.0 (4.3)	1 (1)	1 (0)	14 (2)	146.2 (45.0)	10.4 (2.6)	2.8 (0.8)
	C6	1 (1)	1 (0)	14 (8)	101.6 (47.0)	7.9 (3.8)	1.9 (0.9)	1 (1)	1 (0)	13 (1)	182.7 (101.4)	14.5 (10.0)	3.4 (1.9)
S3	C8	2 (0)	1 (0)	11 (6)	327.9 (349.8)	35.0 (31.8)	6.0 (2.7)	0 (0)	1 (0)	6 (0)	108.1 (48.0)	18.0 (8.0)	1.9 (0.9)
	C10	1 (0)	1 (0)	8 (0)	1931.9 (2798.3)	241.5 (39.2)	22.0 (3.6)	2 (0)	1 (0)	6 (0)	233.5 (11.2)	38.9 (18.7)	2.7 (1.3)
S4	C11	2 (0)	0 (1)	18 (8)	108.7 (39.8)	6.5 (2.0)	1.8 (0.7)	1 (1)	1 (1)	13 (1)	128.9 (26.2)	10.2 (1.8)	2.2 (0.4)
	C12 (12′)	6 (0)	1 (0)	13 (4)	752.9 (566.2)	64.1 (38.9)	12.8 (9.6)	3 (0)	0 (0)	21 (1)	166.1 (51.5)	8.1 (2.6)	2.8 (0.9)
	C13	3 (1)	1 (1)	21 (4)	427.9 (452.8)	23.1 (27.8)	6.7 (7.1)	2 (0)	1 (1)	21 (2)	150.0 (9.4)	7.4 (1.2)	2.3 (0.1)
S5	C14	2 (0)	1 (1)	11 (5)	255.8 (114.1)	26.2 (11.7)	4.6 (2.0)	2 (0)	0 (0)	7 (1)	273.3 (69.8)	41.7 (6.2)	4.9 (1.2)
	C15	2 (0)	1 (1)	13 (2)	279.5 (77.8)	21.8 (3.3)	0.9 (0.3)	0 (0)	0 (0)	6 (0)	463.1 (104.2)	77.2 (17.4)	1.5 (0.3)
	C16	5 (2)	0 (0)	19 (9)	414.4 (336.1)	27.9 (21.7)	7.5 (6.6)	5 (1)	0 (0)	9 (3)	135.7 (7.0)	17.1 (6.2)	2.5 (0.1)
	C17	4 (0)	1 (0)	14 (7)	290.1 (82.4)	23.8 (10.8)	3.5 (1.0)	4 (0)	1 (0)	6 (1)	171.5 (31.4)	27.1 (4.6)	2.0 (0.4)
S6	C18	1 (0)	1 (0)	15 (8)	157.4 (120.0)	10.8 (6.7)	3.2 (2.4)	0 (0)	1 (0)	9 (2)	300.6 (34.0)	36.0 (5.0)	6.0 (0.7)
	C19	2 (0)	1 (0)	29 (1)	435.9 (81.6)	15.1 (3.3)	9.5 (1.8)	1 (1)	1 (0)	13 (3)	829.2 (180.3)	70.3 (38.8)	18.0 (3.9)
	C21	3 (0)	1 (0)	23 (5)	271.8 (56.3)	12.5 (4.6)	5.1 (1.1)	2 (1)	1 (0)	11 (2)	256.6 (46.2)	23.1 (2.7)	4.8 (0.9)
S7	C22	4 (1)	0 (0)	20 (2)	215.6 (47.4)	11.3 (3.3)	3.2 (0.7)	2 (1)	0 (0)	8 (1)	123.8 (17.8)	14.8 (1.7)	1.8 (0.3)
	C23 (23′)	3 (1)	0 (0)	14 (2)	114.0 (4.5)	8.0 (1.1)	2.0 (0.1)	2 (0)	0 (0)	11 (1)	165.9 (13.6)	15.7 (1.2)	2.8 (0.2)
	C24	1 (0)	0 (0)	17 (5)	367.4 (59.2)	23.3 (5.5)	1.7 (0.3)	0 (0)	1 (1)	8 (1)	211.2 (3.8)	27.6 (1.7)	1.0 (0.0)
S8	C25	3 (1)	1 (1)	17 (6)	115.1 (18.3)	7.6 (2.2)	2.2 (0.4)	3 (1)	1 (1)	6 (2)	150.4 (60.6)	27.6 (7.3)	2.9 (1.2)
	C26	2 (1)	0 (1)	17 (4)	179.1 (24.1)	10.8 (2.7)	3.4 (0.5)	1 (1)	1 (0)	7 (3)	554.3 (309.1)	83.9 (39.1)	10.5 (5.8)
	C27	4 (0)	1 (0)	15 (4)	116.1 (11.3)	8.1 (0.9)	2.2 (0.3)	0 (0)	0 (0)	7 (2)	1116.7 (768.5)	155.8 (80.6)	21.1 (14.5)
S9	C28	1 (0)	1 (0)	10 (2)	66.6 (16.7)	6.9 (0.4)	0.9 (0.2)	0 (1)	1 (0)	10 (1)	381.4 (456.8)	35.7 (41.0)	5.2 (6.2)
	C29	2 (1)	0 (1)	19 (6)	92.7 (16.5)	5.3 (1.2)	1.6 (0.3)	2 (1)	1 (0)	10 (1)	341.7 (66.2)	33.0 (7.0)	5.9 (1.1)
S10	C32	2 (0)	0 (0)	23 (2)	114.2 (6.8)	5.0 (0.5)	2.4 (0.1)	2 (1)	1 (1)	5 (4)	71.0 (3.2)	21.8 (17.8)	1.5 (0.1)
	C33	3 (1)	1 (1)	26 (2)	131.4 (30.0)	5.0 (1.0)	2.6 (0.6)	3 (0)	0 (0)	6 (1)	98.5 (45.5)	17.5 (6.0)	1.9 (0.9)
	C34	2 (0)	0 (0)	27 (5)	199.6 (42.8)	7.5 (0.9)	2.0 (0.4)	3 (0)	1 (0)	11 (4)	280.8 (125.1)	29.1 (19.9)	2.8 (1.3)
S11	C35	0 (0)	0 (0)	13 (6)	104.2 (11.1)	8.3 (1.3)	1.5 (0.2)	1 (1)	0 (0)	7 (2)	111.4 (32.2)	15.7 (2.9)	1.6 (0.5)
	C36 (36′)	0 (0)	1 (1)	7 (1)	71.2 (8.8)	11.0 (0.5)	1.3 (0.2)	1 (0)	0 (1)	7 (1)	216.1 (204.8)	32.2 (28.4)	4.0 (3.8)

[a] Mean (SD) of the ventilation rates, number of students, and numbers of opened windows and doors during the occupied lessons in the classrooms.

time the indoor air temperature in the classrooms fell outside range A, and 10% of the time fell outside range C. Only 68% and 6% of the classrooms maintained the indoor air temperature always within range C and range A, respectively (Table 3). It is hence clear that during the pre-lockdown period the indoor air temperature was on the cold side, and the thermal conditions in the classrooms were not satisfying, possibly causing discomfort to the students and the teachers. Using the adaptive model of thermal comfort prescribed in the ASHRAE 55 standard [60] to assess the average air temperature in the classrooms, it is shown that before the lockdown, five of the 31 (16%) classrooms did not comply with the 80% acceptability limits, and nine (29%) did not comply with the 90% acceptability limits, where all of them were too

Table 5
Univariable and multivariable associations between VR_p and occupancy, opening of windows and doors in the classrooms, and visits (pre-versus post-lockdown).

Variable	Univariable			Multivariable		
	Exp (β)	95% Wald CI (lower, upper)	P	Exp (β)	95% Wald CI (lower, upper)	P
Occupancy	0.934	0.919, 0.951	<0.001	0.938	0.915, 0.963	<0.001
Window	1.022	0.925, 1.130	0.688	1.081	0.994, 1.176	0.068
Door	1.302	0.909, 1.865	0.149	1.218	0.881, 1.684	0.234
Visit	1.925	1.409, 2.633	<0.001	1.302	0.928, 1.827	0.126

cool. However, during the school visits it was often observed that students were wearing their jackets inside the classrooms, indicating that their actual thermal sensation may be cooler compared to the model if they wear normal indoor clothes.

Comparing the outdoor air temperature measured during the post-lockdown period with the pre-lockdown period, a significant increase was observed among the schools (Table 3). However, no significant difference was found in the indoor air temperature before and after the lockdown. Nevertheless, a decrease in the average time of indoor air temperature outside the ranges A, B, and C of the Dutch Fresh Schools guidelines was observed (Table 3). Although the percentage of classrooms with indoor air temperature all the time fulfilling range A increased by 10%, for range B the number did not change, and for range C it decreased by 10%. Moreover, after the lockdown, not only there were more than 30% of the classrooms with an indoor air temperature colder than the lower limit of range C, but also 10% of them had it warmer than the upper limit of range C, both indicating negative impacts on occupants' thermal comfort. The variations in the indoor air temperature were possibly affected by the outdoor environment. According to the ASHRAE 55 adaptive thermal comfort model [60], three (10%) classrooms did not comply with the 80% acceptability limits, and eight (26%) did not comply the 90% acceptability limits.

In general, keeping the windows and doors opened on the one hand helped increasing outdoor air supply compared to the pre-pandemic era [4], yet on the other hand also harmed the thermal conditions for the students, in particular during the heating season. If the schools had been open in the winter, during which outdoor air temperatures can be much lower than the ones that were measured in this study, the temperature indoors would have been even colder assuming the same measures were taken. Such thermal comfort related problems resulted from improving ventilation by means of increasing opening windows and doors have been extensively reported by recent field studies, both before and during the COVID-19 pandemic [41,61,62].

4.3. Limitations

First, the results are limited because in this study almost all the school visits were conducted during a part of the heating season, and thus the situation in both the lockdown period (during the winter time) and the non-heating season were rarely represented. Also, each school visit only lasted for one day, and therefore, not all possible occupancies and behaviors in the classrooms were included in the study. This can have affected the results of the indoor environmental measurements. In particular, the ventilation rates that can be reached with mechanical ventilation (if present) without opening the windows and doors, could not be determined. The monitoring of the outdoor environments was also limited in time, especially during the first school visits, in which not enough data was collected to fully represent the fluctuations of the outdoor environmental parameters, and consequently its effects on the indoor environmental conditions. Nevertheless, by selecting the same classrooms before and after the lockdown, and monitoring the environmental parameters at different locations in the classroom as well as noting the number of occupants per lesson, a comparison could be made of the situations before and after the lockdown.

Second, the intention of the study was to study "normal" conditions before the lockdown, and compare them with "adjusted conditions caused by COVID-19 measures" in schools with different ventilation regimes. Unfortunately, the "normal" situation before the lockdown

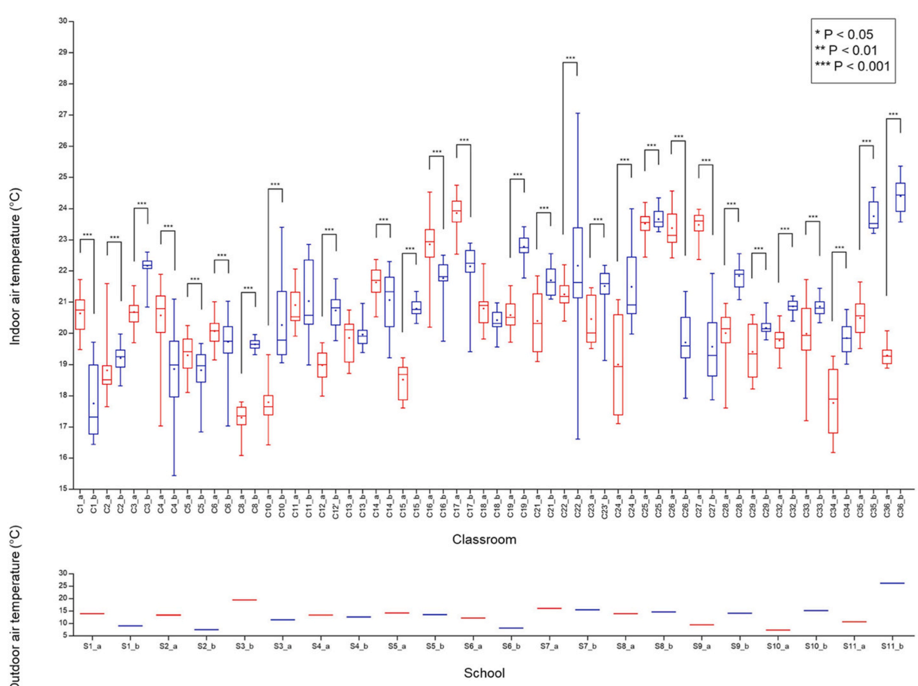
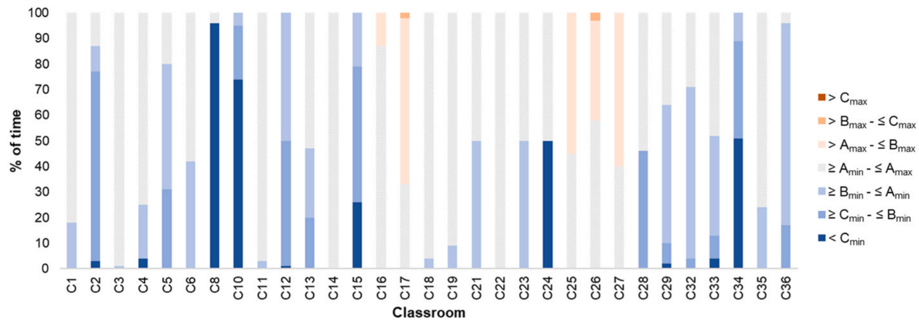
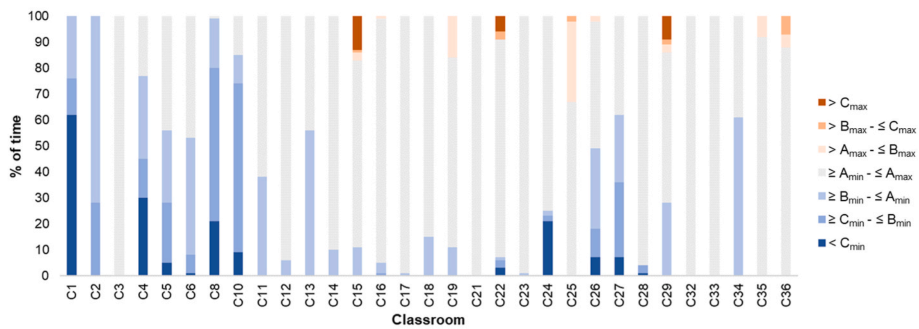


Fig. 6. Indoor and outdoor air temperatures (a: pre-lockdown period; b: post-lockdown period). Above: box and whiskers plot of indoor air temperature inside the classrooms (P: Mann-Whitney *U*-tests between pre- and post-lockdown period); Below: average outdoor air temperature at each school.



(a)



(b)

Fig. 7. Time distribution of indoor air temperatures during occupied lessons in the classrooms among different categories of Dutch Fresh Schools guidelines: (a) pre-lockdown; (b) post-lockdown.

turned out to be already influenced by COVID-19 measures, namely "opening windows and doors" as much as possible, regardless of the ventilation regimes: natural or mechanical (mechanical supply only, mechanical exhaust only, both mechanical supply and exhaust). This also limited further investigation on the differences among ventilation regimes.

Third, the calculation of ventilation rates in the classrooms was based on a 5-min period of each occupied lesson that fulfilled the steady-state condition, and a fixed number of occupants per lesson, of which the CO_2 generation rate per person was estimated as one fixed value for all occupants, which in fact differs for each person with factors such as sex, age, and activity, etc. [63]. Therefore, such estimation might lack accuracy, since this study has involved students spanning a certain age difference, as well as different types of secondary education with both theoretical and practical settings.

Finally, occupants' subjective assessments on the IEQ conditions of the classrooms have not been collected in this study. Consequently, the analyses related to comfort issues were purely based on physical measurements, observations, using existing standards and guidelines as the major references, which however, are mostly based on the models of adult occupants. Hence, such results may deviate from the actual perceptions of the students [58,64,65].

5. Conclusions and recommendations

In this field study, surveys were conducted among 11 secondary schools in the Netherlands from October 2020 to June 2021, both before and after a national lockdown that lasted from December 15, 2020 to March 1, 2021, to investigate the CO_2 concentration, ventilation rate, and thermal condition in the classrooms. In the end, the results of 31 classrooms were reported, and the conclusions and recommendations are drawn as follows.

5.1. Conclusions

Before the lockdown, the classrooms were used under normal occupancy of an average of 17 students, with windows and doors kept. Only one sixth of the classrooms could maintain the indoor CO_2 concentration below the preferred level A of the Dutch Fresh Schools guidelines, and in 42% of the classrooms it exceeded the upper limit of acceptable indoor CO_2 level during some periods. Meanwhile, the ventilation rate per person (VR_p) in 13% of the classrooms did not meet the minimum requirement (6 l/s/p), while only 55% of the classrooms achieved the level recommended by different standards and guidelines (10 l/s/p).

After the lockdown, the average occupancy decreased to 10 students per classroom, while the operation of windows and doors remained similar. Although the indoor CO_2 concentration decreased significantly, in terms of ventilation rates, only VR_p showed a significant increase. The total ventilation rate per classroom did not change significantly. Over 90% of the classrooms reached a VR_p higher than the recommended level of 10 l/s/p. The GEE analysis showed that the increase in VR_p between pre- and post-lockdown periods was mainly associated with the decrease in occupancy, rather than the operation of windows and doors.

Thermal conditions in the classrooms were, according to the guidelines, not satisfying during both the pre- and post-lockdown periods. Before the lockdown, the air temperature in the classrooms was generally on the cold side, most likely caused by the measure of opening windows and doors constantly, where 32% of them had the indoor air temperature deviating from the required range C. After the lockdown, the percentage increased to 42%, with both unacceptably low and high levels being observed in several classrooms. Such conditions can possibly cause discomfort to the students.

It is hence concluded that with windows and doors kept open, both the ventilation and thermal conditions in the classrooms did not fulfill the recommended standards and guidelines at all times, and need to be further improved. Reducing occupancy can indeed increase the ventilation rate per student in the classrooms, when the total amount of outdoor air supply achieved does not vary greatly. However, this might not be an immediate solution for the schools to implement, given limited space and staff.

5.2. Recommendations

Overall, more controllable and flexible ways for improving indoor air quality and thermal comfort in school classrooms are needed. Well-designed mechanical ventilation systems that can provide sufficient air supply per occupant and can be demand controlled according to occupancy and activities, are needed [66,67]. This is not only essential for maintaining good indoor air quality, but also for ensuring a thermally comfortable indoor environment in the school classrooms.

Previous studies have also indicated the potential of personalized environmental control systems, such as personalized ventilation systems, as a possible solution for improving the local indoor environmental quality of the occupants and ensuring their health and comfort. However, further development is needed concerning the particular scenarios in school classrooms, as well as the preferences and needs of children [68,69].

CRediT authorship contribution statement

Er Ding: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Dadi Zhang:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **Amneh Hamida:** Writing – review & editing, Investigation. **Clara García-Sánchez:** Writing – review & editing, Formal analysis. **Lotte Jonker:** Writing – review & editing, Investigation. **Annemarijn R. de Boer:** Writing – review & editing, Formal analysis. **Patricia C.J.L. Bruijning:** Writing – review & editing, Investigation. **Kimberly J. Linde:** Writing – review & editing, Investigation. **Inge M. Wouters:** Writing – review & editing, Investigation. **Philomena M. Bluyssen:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2022.109922.

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