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Experimental assessment of impact of different ventilation modes on cognitive and academic performance: A study based on classrooms in Türkiye

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ABSTRACT

In closed spaces, such as classrooms, poor ventilation, indoor exposure to CO_2, and non-optimal humidity and temperature conditions are global concerns associated with health and performance. This study experimentally assesses the effects of different ventilation modes on the air quality parameters and cognitive and academic performances of 120 s-grade primary school children in two buildings with different characteristics during heating and non-heating seasons. Based on a retrospective analysis of 455 primary schools in Türkiye during 2017–2018, the study was conducted in six classrooms of the two representative school buildings. Indoor air quality monitoring and performance (of the students) assessment was carried out from December 9, 2019, to September 28, 2020. The non-heating season measurements were conducted during the COVID-19 pandemic. According to our findings, the traditionally constructed school without energy efficiency regulations exhibited the worse scenario. The success percentages of arithmetic attention in both traditional and natural ventilation modes were significantly lower in the non-heating season than in the heating season, which indicates the impact of using a facemask inside a classroom during cognitive tasks. This study demonstrated that the heating season is more critical than the non-heating season in terms of ventilation of closed spaces.

Abbreviation list

IAQ	Indoor air quality
CO_2	Carbon dioxide
T_S	Traditional school
S_S	Sustainable school
VAV	Variable air volume system
TVC	Traditionally ventilated classroom
NVC	Naturally ventilated classroom
MVC	Mechanically ventilated classroom
ISO	International Organization for Standardization
CEN	European Committee for Standardization

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ISO	International Organization for Standardization
ASHRAE	American Society of Heating, Refrigerating, and Air-conditioning Engineers
RH	Relative humidity
T	Temperature
DCV	Demand-controlled ventilation
ST	Stroop test
SCT	Star counting test

1. Introduction

Children spend most of their time in schools that have indoor air quality (IAQ) issues [1]. Thus, poor ventilation modes, indoor exposures to carbon dioxide (CO_2), and changes in humidity and temperature in classrooms are global concerns associated with health, academic performance, and comfort [2]. Thus, the impact of IAQ on cognitive and learning activities in schools has been studied extensively in the literature [3]; however, the findings vary considerably; there were discrepancies in terms of age/health/fitness participants, cognitive and performance tests [4–6], test environments [7], and exposure scenarios [8,9]. Moreover, current studies lack statistical power because most IAQ experimental studies were conducted with only 10–30 participants [10]. Only a few studies compare different ventilation modes in generalized typical school environments [11,12]. Most of these studies analyzed IAQ parameters according to the sustainability guidelines and standards, focusing on associations between the CO_2 concentrations, ventilation rates of classrooms, and student performance in naturally ventilated schools [13].

Additionally, the studies indicated that schools could not rely on opening windows and doors to satisfy the minimum IAQ conditions to promote a healthy environment for learning. The seasonal effects and building characteristics were not examined comprehensively and simultaneously because of the limited number of parameters. Particular attention should be paid to younger children, who spend more time indoors and are more vulnerable to air pollution than high school and university students [14].

Consequently, there is an essential need to assess the IAQ of preschool and primary school environments concerning seasonal differences, ventilation mode variability, and school and room characteristics and their impact on cognitive abilities and academic performance. This study aims to experimentally assess the effects of different ventilation modes on the air quality parameters and cognitive and academic performance in different school buildings (with individual characteristics) during heating and non-heating seasons. Our study also explores the associations between building characteristics, different ventilation modes, and impacts of CO_2, temperature, and humidity on the perceived IAQ to find an effective ventilation strategy and improve individuals' cognitive and academic performances in a close environment. Moreover, the monitoring during the non-heating season was conducted during the COVID-19 Pandemic, during which the students wore masks, which could be considered another stimulus affecting the performance results. In the monitoring during the heating season, the COVID-19 Pandemic was not declared by the Turkish Ministry of Health.

2. Background

Due to the COVID-19 pandemic, there is a growing interest in studying the IAQ of environments where we live and work [15]. School environments are the most common venues that require improved hygienic and ventilation conditions. Previous studies have shown that increased health symptoms, decreased attention levels, high student absenteeism, and decreased scores on academic achievement tests are affected mainly by the ventilation modes and levels of classroom air quality [16]. Reviewing the current literature, starting from the earliest study in 1982 [17], revealed that the IAQ studies for schools could be grouped into three categories: (i) manipulating the ventilation rates by changing the CO_2 concentration levels [18–22], (ii) monitoring the air quality parameters by changing the natural ventilation strategies [8,13], (iii) plotting the quantitative results of the performance and cognitive impacts of air quality parameters in a mixed mode consisting of natural and mechanical ventilation [7,12,23,24]. It is important to note that these studies were mostly conducted in secondary and high schools and neglected the building characteristics.

There is scarce data on IAQ's cognitive impact in primary schools and nurseries; thus, collecting cognitive data for such cases is more difficult. In the three groups mentioned above, the cognitive and performance impact of CO_2 remained varied and inconsistent. The common issue in the tested hypotheses highlighted that noticeable physiological effects were only observable above 10,000 ppm, and the changes in cognitive work did not appear until after prolonged exposures. Thus, Du et al. [10] suggested the following hypothesis to deal with the inconsistency of cognitive results: “When the mental load required in a cognitive test surpasses the maximum mental efforts that a test participant can make, their performance will drop” (p.1076); they also suggested considering the effects of other environmental stimuli on cognitive function and performance. In addition to poor air quality, classroom attributes and building characteristics also impact the students' cognitive function and performance [25]. However, no studies focus on the cognitive impact of different ventilation modes in different building characteristics. Moreover, in Türkiye, the available data regarding the IAQ in schools and its impact on cognitive performance are limited to simulation analyses, small sample laboratories, or test chamber cases. Within this framework, our study is an initial attempt to consider building characteristics and interactions between different air quality parameters (CO_2, temperature, and humidity), cognitive and academic performance, and ventilation modes.

3. Materials and methods

3.1. Study setting and participants

In Türkiye, the Ministry of Public Works developed a standard design for schools; this design was implemented in all provinces until 1970 [26]. In 1980, the Provincial Directorates of National Education developed updated projects with only minor differences from province to province. Following the European Energy Efficiency Directives, with the Energy Performance Regulations [27], in 2000, Türkiye began to adopt energy efficiency measures for its stock of school buildings. However, many school buildings were constructed in the second half of the 20th century, when the building requirements had not yet focused on energy efficiency [28].

To meet the needs of the current study design, a retrospective analysis was performed in 2017–2018, in which the findings of energy efficiency performance analyses that were carried out for public buildings in Türkiye were collected. The energy efficiency data of 455 Turkish primary schools were also collected through energy simulation analyses. The ventilation conditions and classroom characteristics were obtained through direct observations, thermal camera photography, and surveys. We found that most of the school buildings (80 %) used natural ventilation and had similar massing typologies concerning geometry, façade design, and other architectural characteristics, regardless of the wide range of climatic conditions and geographical locations of the provinces.

Regarding the typology literature, the school massing corresponds to a double-loaded corridor plan of atrium massing. Depending on the student number, dimensions of classrooms, size of the lot, topography, and surrounding areas, there are also modular definitions of "massing typology" with respect to changes in ground floor areas and the number of stories. Fig. 1 illustrates the abstract models of the most commonly used examples to portray the general organization of a typical school massing in Türkiye. However, the school buildings (nearly 20 % of the total schools) constructed after 2000 use mechanical ventilation and have sustainable characteristics regarding the materials used, wall and floor thickness, classroom plan layouts, and integration of natural ventilation using mechanical systems. Furthermore, the classroom dimensions are bigger, with higher ceilings, increased window layouts (enabling natural ventilation), and natural lighting.

In terms of construction, typology, and plan layout, this study chose two representative and typical school buildings [one traditional (T_S) and one sustainable (S_S)] to monitor the IAQ parameters in different ventilation modes; then, we associated these parameters with the students' cognitive function and learning outcome. These private schools are located in Ankara, Türkiye, at 39°57′ N, 32°53′ E (elevation 891 m). Ankara has a hot Mediterranean/dry-summer subtropical climate that is mild, with moderate seasonality [29]. Summers are dry and hot due to the domination of subtropical high-pressure systems, while winters experience moderate temperatures and fluctuating, rainy weather due to the polar front [30]. The warmest month is June, with an average temperature of 20.6 °C. The coolest month (on average) is January, with an average temperature of −2.8 °C.

The traditional school building was built in 1997, with bricks and concrete main construction materials. There were 29 classrooms in the building. The school had a total gross area of 4200 m^2; it was heated using a central heating system by water-filled radiators placed under the windows and ventilated using the manually operated windows. Fig. 2a illustrates the external view of the school,

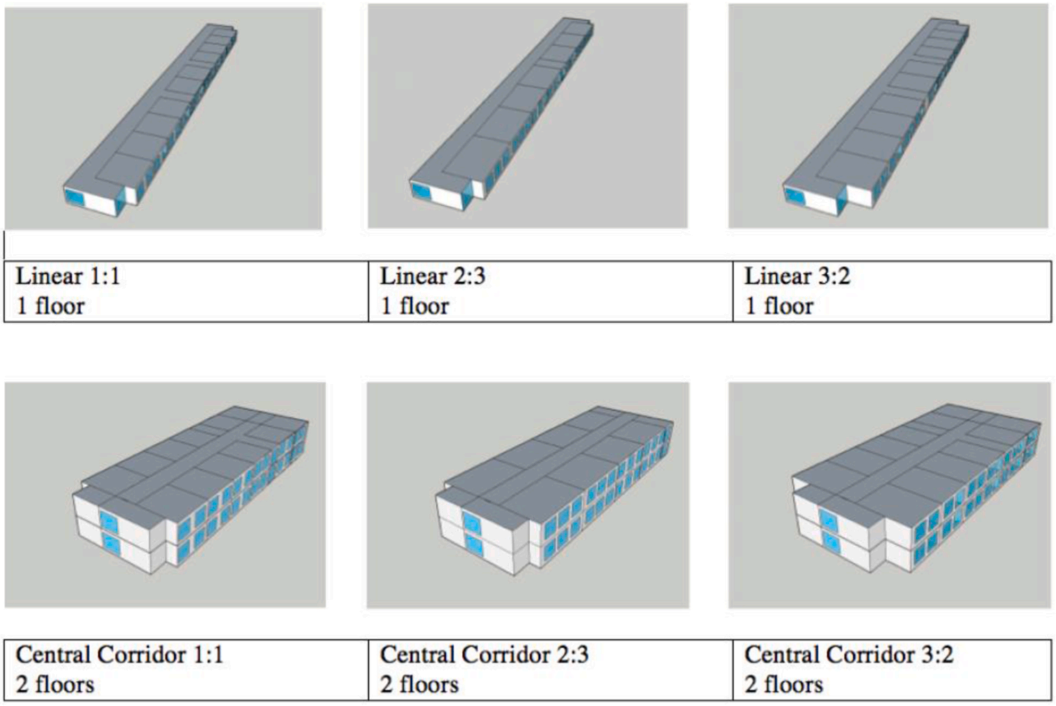


Fig. 1. Abstract models of the most commonly used typical school massing in Türkiye (Author, 2020).

Fig. 2. (a) External view of the traditional school; (b) Classroom floor plan of the traditional building.

and Fig. 2b demonstrates the classroom floor plan of the building. During our study, 522 primary school children and 74 teachers were in this building.

The second representative building, the sustainable school building, was built in 2009 with aerated concrete blocks and concrete construction. In this building, there were 21 classrooms, and the school had a total gross area of 4800 m^2. Fig. 3a illustrates the external view of the school, and Fig. 3b illustrates the classroom floor plan of the building. The school's heating, cooling, and air-conditioning were achieved using a variable air volume system (VAV). In both the school buildings, (i) the occupancy of the school

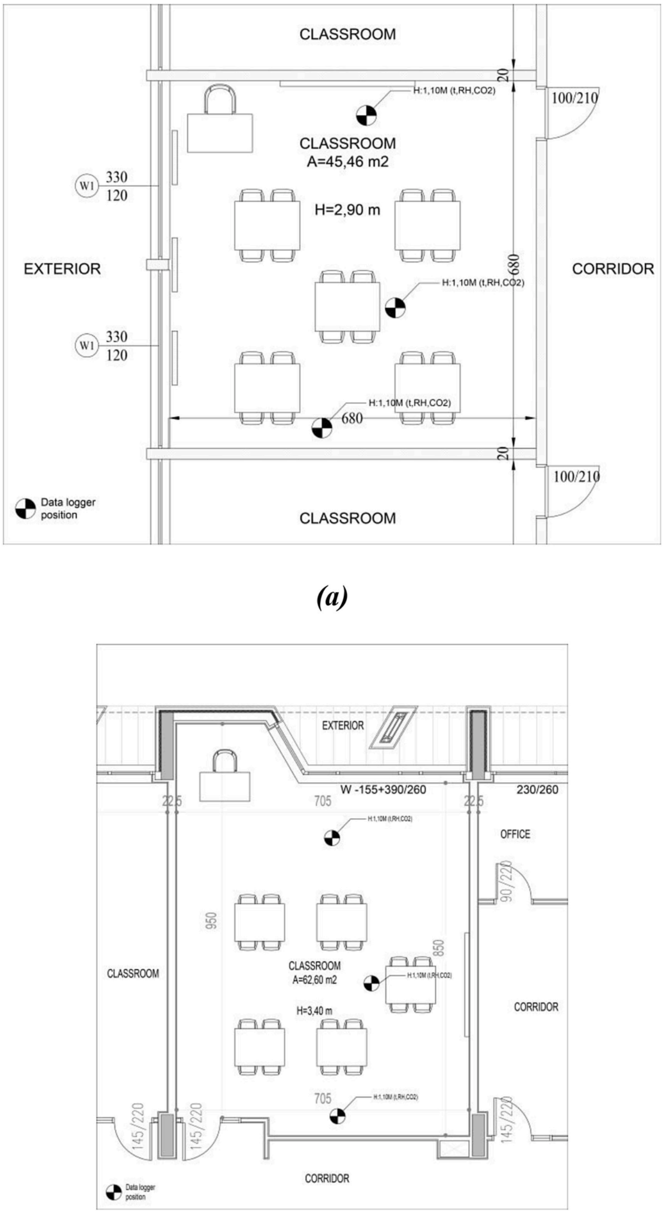
(a)

(b)

Fig. 3. (a) External view of the sustainable school; (b) Classroom floor plan of the sustainable building.

occurred during the day, (ii) the classes were scheduled from 08:15 h to 16:15 h, with six small breaks of 10 min and one long lunch break of 50 min; (iii) weekends and summer holidays, from June 1 to September 1, were assumed to be unoccupied, thereby using only primary heating, (iv) it is assumed that there was no hot water demand, (v) and effects of shade provided by neighborhood trees, buildings, and other structures were assumed to be negligible.

The analysis of different ventilation modes in each school building was based on three identical second-grade primary school classrooms. All classrooms were northwest-oriented. The classroom plan of the traditional type of school, with the furniture, is illustrated in Fig. 4a. The three classrooms in this building had a total area of 45.46 m^2 and a height of 2.90 m. The classrooms' window openings were along the room's long sides. For the experimental measurements of the present study, one of these classrooms was equipped with a heat recovery unit using a 70 %-efficient heat recovery exchanger. The unit drew fresh air directly from the outdoor environment, conditioned it, and circulated it in the classroom to keep the classroom temperature stable. The classroom floor plan of the sustainable school (with the furniture) is illustrated in Fig. 4b. The three classrooms in this school building had a total area of 62.60 m^2 and a height of 3.40 m. The windows were manually operable (in the form of a clerestory window) along the bottom of the



(a)

(b)

Fig. 4. Classroom plans: (a) Plan of the traditional school, CAD-drawn; (b) Plan of the sustainable school, CAD-drawn (Author, 2020).

glazed side. In the sustainable school, each classroom had a glass door that opened to the courtyard garden. No shading device was present on the windows in either school. Each classroom (in both schools) was used by 20 children aged 7–8 years during both the heating and non-heating seasons. In total, 120 healthy second-year grade primary school children, 56 girls and 64 boys, participated in this experimental study. The same children were in the same classrooms during both seasons. All the children were non-allergic to CO_2 and were healthy.

3.2. Study design

The experimental study monitored the IAQ parameters (temperature, humidity, and CO_2) in six classrooms during the heating and non-heating seasons and measured the students' cognitive performance through visual and arithmetic attention tests, along with their academic performance. The monitoring was carried out in terms of long-term measurements: from December 9, 2019, to January 14, 2020, representing the heating season, and from August 17, 2020, to September 28, 2020, representing the non-heating season. During the non-heating season, all children wore facemasks during school hours. The start and end of monitoring corresponded to the beginning and end of a new teaching unit; this helped directly associate the temperature, humidity, and CO_2 measured in each classroom with the children's academic achievements. The following three experimental ventilation strategies were designed for three classrooms in each school: (1) traditionally ventilated classroom (TVC), (2) naturally ventilated classroom (NVC), and (3) mechanically ventilated classroom (MVC) (Fig. 5).

The traditionally ventilated classrooms acted like a control group; the teacher ventilated the room by manually opening the operable windows as usual. The teacher did not usually open doors or windows during class hours, except for opening them every 10 min after every 40 min. During the heating season, the teacher and children tended to keep the windows and doors closed because of the cold outdoor weather conditions. This mode can be defined as a free-pattern ventilation strategy. In the second ventilation strategy, the classroom was ventilated every 20 min by opening the operable windows. The windows were kept fully open for 10 min and also during all break times. The heat recovery unit was set for the heating and non-heating modes in the mechanical ventilation strategy. The unit had a self-control system composed of sensors to control the humidity, temperature, and CO_2 that operated the changing classroom air conditions according to the set conditions. The unit had a control panel with an on-off switch mounted on the wall, provided to the teachers for control. The unit was activated 1 h before the class started.

The indoor air CO_2 concentration levels during the heating and non-heating seasons were set within the comfort ranges of 1000 ppm according to the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) [31]. Humidity and temperature were set according to reference ranges provided by the ASHRAE [32] and European Committee for Standardization (CEN) [33], to 50 % relative humidity (RH) and temperatures (T) of 21–23 ˚C for heating and 23–26 ˚C for non-heating seasons. In the first two strategies, all operable windows remained fully opened during the break times. In the third strategy, windows were opened only during the last break. Although there have been conflicting studies regarding mechanical ventilation during the COVID-19 pandemic, all guidelines emphasized the importance of ventilation, but with a specific ventilation rate [34]. Thus, in this study for the non-heating season, the operation of the unit was carried out based on the "ASHRAE *Covid-19 (Coronavirus) Preparedness Resources* and *ASHRAE Position Document on Airborne Infectious Diseases*" [35,36] to eliminate the risk of virus transmission. Furthermore, the amount of outdoor air in the heat recovery unit in the ventilation system was increased, and demand-controlled ventilation (DCV) was disabled.

The air quality data were collected during the occupied periods, with an average of 25 consecutive days for each school during each season. The intervals of the recordings were set at 5 min. A Testo 480 data logger was used with a measurement range of 0–10000 ppm (resolution: 1 ppm CO_2), from −100 ˚C to 400 ˚C (resolution: 0.01 ˚C, 0–100 % RH), and (resolution: 0.1 % RH). The devices were placed at three different locations at the height of 1.1 m, far from any heat source and without disturbing the class activities (see Fig. 4a and b). The devices were calibrated regularly according to the manufacturer's instructions during the monitoring periods. The locations are illustrated in Fig. 3. Since the two schools were located in a green campus environment, 11 km away from the city center, the outdoor CO_2 was assumed to be 350 ppm, according to the CEN [33].

3.3. Quantification of cognitive and academic performance

De Jong and Das-Smaal [37] explained that "attention is assumed to have a wide range of influence on many aspects of cognitive functioning" (p. 597). In this study, visual attention and arithmetic attention tests were used to quantify children's cognitive function. The tests were conducted at each season's six-week monitoring period's beginning, middle, and end. For the visual attention test, the Stroop world-color test was used. For our study, the Stroop test (ST) was used so that the difficulty of the test was appropriate to the age and level of the children as per our consultation with the graduate school, school administration, and teachers. The test included eight trial rows of real-world color stimuli. The children were asked to identify the color tag in each row of the displayed colored rectangles; they were provided 5 s for each row (see Appendix A, section A1). The success was represented as 100 % for the maximum performance value.

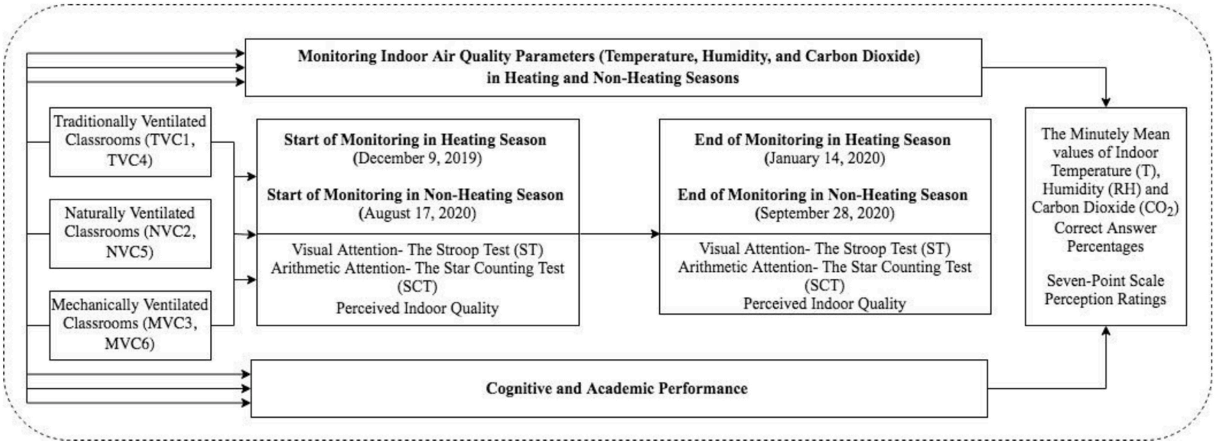


Fig. 5. Procedure diagram of the study illustrating three experimentation ventilation strategies (Author, 2020).

For the arithmetic attention test, the star counting test (SCT) was used [38], which was developed to make it appropriate for the age and level of the children (as consulted with the graduate school, school administration, and teachers). The test score is the total correct number of each trial row. The SCT was developed based on working memory, referring to a temporary storage and knowledge processing system [34]. It had two parts, each composed of eight rows of stars (see Appendix A, section A2). Each row showed plus and minus signs in between the stars. The following instruction was given to the children in the first part: "Start from left to right. Find the result by adding the stars to the given number row-wise if there is a '+' sign, or subtracting the stars from the given number if there is a '−' sign." The plus and minus signs had the opposite meaning in the second part. Thus, the following instruction was given to the children: "Start from left to right. Find the result by adding the stars to the given number row-wise if there is a '−' sign, or subtracting the stars from the given number if there is a '+' sign." Each part had to be completed in 10 min. The test score was the total number of correct answers for each part and was represented as 100 % for the maximum performance value. There was a six-week break between the tests to eliminate the learning effect. To eliminate the order effect, the order was changed for the tests performed at the end of the monitoring period.

The children's learning outcomes were measured as their academic achievement during the six weeks of each season. Each measurement started with the beginning of each unit encompassing the theoretical and practical knowledge of qualitative (such as reading, logical reasoning, and comprehension in Turkish and English language) and quantitative (such as math and geometry) lessons. For each grade of primary school in Türkiye, standardized test schemes are defined by the Turkish Ministry of Education to evaluate and quantify students' academic performances. In this study, each child's qualitative and quantitative scores were obtained from the teachers that used the classrooms (for each ventilation mode) at the beginning and end of the unit to analyze the effects of ventilation modes on the student's performances. Our study used, examined, and compared these scores, expressed by the correct answers and represented as a percentage (100 % for the maximum performance value).

In addition to the objective measurements explained above, the study also conducted subjective measurements (see Appendix B). The children were asked to rate their perception of the IAQ comfort level on a 7-point numerical scale each week in the last class hour every Friday. The scale that was used to collect temperature perceptions was: −3 (cold), −2 (cool), −1 (slightly cool), 0 (ok), 1 (slightly warm), 2 (warm), and 3 (hot). The air humidity perception of children was collected based on their air-moisture ratings: −3 (very humid), −2 (humid), −1 (slightly humid), 0 (comfortable), 1 (slightly dry), 2 (dry), and 3 (very dry). Their CO_2 concentration level perceptions were collected based on their air-freshness ratings: −3 (very stale), −2 (stale), −1 (slightly stale), 0 (normal), 1 (slightly fresh), 2 (fresh), and 3 (very fresh). During the monitoring, the children were performing learning activities, and the clothing insulation was 0.5 for the non-heating season and 1.0 for the heating season. Moreover, days of absence, if any, of the students due to upper respiratory tract infection were also recorded by the teachers for each classroom during both measurement seasons.

3.4. Data analyses

This study set the acceptable CO_2 concentration limit at 1000 ppm based on the above-mentioned international reference values. An 80 % acceptability limit of temperature was considered based on the parameters set by CEN [33]. The mean values for the indoor-air comfort parameters (CO_2 concentration, temperature, and humidity), attention scores, learning outcome performance percentages, and perceived IAQ mean ratings for both seasons were compared. The IAQ differences among the three ventilation modes for each school were analyzed using the non-parametric Kruskal–Wallis test, and the differences between the two schools for each ventilation mode were analyzed using the non-parametric Wilcoxon Rank Sum test that was used with Bonferroni corrections because the measured CO_2 concentrations in the classroom did not follow a normal distribution. In each school, the CO_2 concentration level in each classroom was analyzed concerning the ventilation mode, seasonal change, air temperature, and humidity. For each season, a one-tailed *t*-test was used to compare the statistical differences between the same ventilation modes of the two schools with respect to the cognitive and academic performances of the children. One-way analysis of variance (ANOVA) was used to analyze any significant differences in the mean values of the perceived IAQ among the three classrooms of one school and the one-tailed t-tests between the two classrooms of the same ventilation mode of the two schools.

Further pairwise comparisons among the three classrooms were carried out using TUKEY Post Hoc comparisons to calculate which of the means differed from one ventilation mode to another. For all statistical analyses, a significance level of 0.05 was considered. All analyses were performed using IBM Statistical Package for Social Sciences (SPSS) version 21.

3.5. Ethics approval

The Ankara Governorship District Directorate approved the study of National Education. The ethical permission for the study was obtained from the university's ethical review board. The participants' families, school administrations, and teachers provided us an informed consent before we collected the data.

4. Results and discussion

4.1. Air quality monitoring

The mean values of indoor Temperature (T), Humidity (RH), and CO_2 for each classroom of the two schools are illustrated as the seasonal minimum, maximum, mean, median, standard deviation values. The table also shows correlation coefficient values between different scenarios and each IAQ parameter. Each air quality parameter was significantly associated with varying ventilation modes regardless of the season; the larger correlation coefficient, the more impact of the ventilation mode on the parameter. As shown in Table 1, after 20 min of occupation period (of 20 children) in both schools, except for the mechanical ventilation mode, the CO_2 concentration reached the limit of 1000 ppm. Regardless of the season and the school type, the highest CO_2 concentration level

Table 1

Minutely mean values of indoor temperature (T), relative humidity (RH), and CO_2 concentration for each classroom.

	Primary School	T_S						S_S					
	Classroom	TVC1		NVC2		MVC3		TVC4		NVC5		MVC6	
	Season	H.	NonH.	H.	NonH.	H.	NonH.	H.	NonH.	H.	NonH.	H.	NonH.
T (°C)	Min	20.2	23.2	16.8	21.3	18.5	20.3	19.1	21.1	16.8	21.5	18.5	21.4
	Max	26.3	27.7	25.6	25.5	25	24.7	27	25.5	25	26	25	24.7
	Mean	24.2	25.4	24.1	24.2	23	22.9	25	24.2	24.09	23.7	23.1	23.4
	Median	24.6	25.4	24.3	24.4	23.2	23.2	26	24.2	24.3	23.7	23.3	23.2
	StDev	1.3	0.98	1.1	0.71	1.6	1.3	1.1	0.74	1.1	0.91	1.5	0.96
	Coeff.	0.771*		0.600*		0.565*		0.474*		0.525*		0.230*	
RH (%)	Min	29.4	29.8	32.2	27	24.9	27	30.9	29.8	32.2	24.9	25	31.2
	Max	42	40	42.9	35	40.4	49.8	44	40.9	42.9	32.4	33.4	49.5
	Mean	34.9	34	36.1	30.4	28.8	35.9	36.5	34.1	35.8	28.3	29.8	38.1
	Median	34.5	33.8	36.1	30.2	29	35.1	35.7	33.8	36	28.9	29.5	37.3
	StDev	3.6	2.5	2.2	1.9	2.1	1.9	3.4	2.5	1.8	1.5	1.9	4.7
	Coeff.	0.688*		0.512*		0.791*		0.314*		0.366*		0 0.504*	
CO_2 (ppm)	Min	580	580	732	632	585	585	532	524	643	6532	585	585
	Max	3381	2166	2655	1736	1412	1331	2655	2166	1950	11,736	1573	1 1580
	Mean	1770.4	1308	1459.3	1373	1030	1050	1459.8	1293	1395	1 1368.1	1014.4	1150
	Median	1834	1345	1439	1417	1066	1080	1423	1264	1257	1406	1 1066	1179
	St.Dev	807.6	384.1	468.5	205.6	236.3	222.2	423.9	375.7	385.4	2202.2	2 20.8	1792
	Coeff.	0.559*		0.725*		0.578*		0.381*		0.456*		0* 0.130*	

Note: H is the heating season; Non H is the non-heating season; StDev is standard deviations; Coeff is the correlation coefficient.

$*p < 0.05$.

(3381 ppm in the heating season and 2655 ppm in the non-heating season) was obtained in the traditionally ventilated classroom of the traditional school. In both schools, in the traditionally ventilated classrooms (TVC1 and TVC4), the CO_2 levels increased above the recommended limit values.

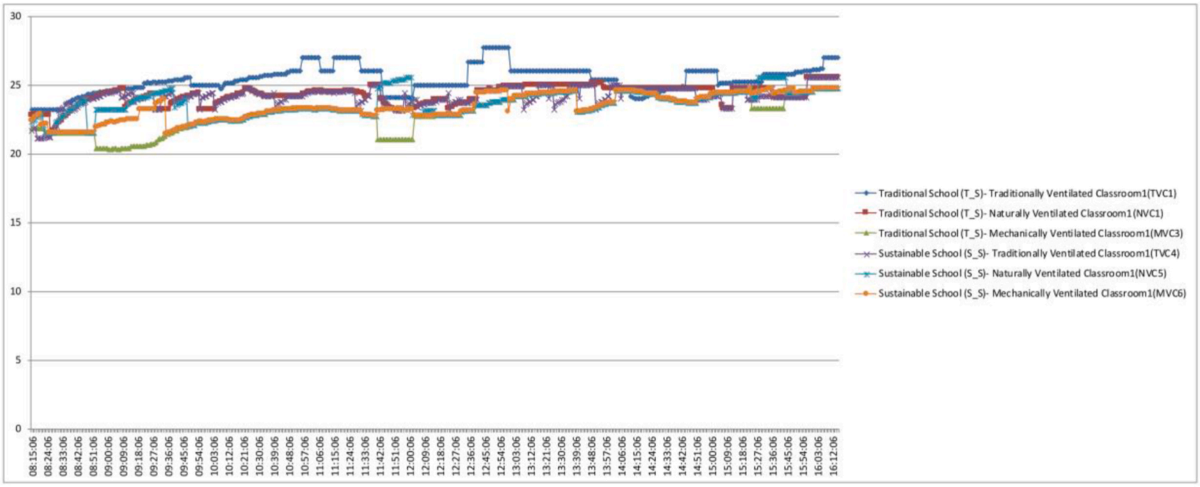
This finding is in line with previous studies, which tested the IAQ of school buildings having no proper and adequate ventilation and arbitrary window opening patterns as poor. Although the traditional ventilation mode in both schools showed high CO_2 levels, there were significant variations in the CO_2 concentrations in both seasons (according to paired *t*-test; $t = 7.6704$, $df = 480$, $p = 0.000$ for heating seasons and $t = 3.3066$, $df = 480$, $p = 0.000$ for non-heating season). The CO_2 levels were usually higher in TVC1 than in TVC4 because sustainable buildings provide acceptable levels of IAQ [38]. However, this study showed that the sustainability character is not enough to cope with the CO_2 levels. There is a critical need to establish preferred ventilation modes to achieve decreased CO_2 concentrations. Although there was a slight decrease in CO_2 levels from the heating season to the non-heating season in all the classrooms, except the mechanically ventilated classrooms (MVCs), the values were still above the acceptable limits. This decrease was mainly due to the outdoor meteorological characteristics, which affected the manual window-opening patterns. However, as stated in the literature [8], natural ventilation alone is not an effective strategy because of its difficulty to control. Moreover, similar to the previous studies [39,40], in this study, because of the manual window-airing mode, the NVC2 and NVC5 classrooms had lower indoor temperature values during the heating season and higher indoor temperature values during the non-heating season, which resulted in thermal discomfort.

Fig. 6 illustrates the daily mean profile of the heating season for all the classrooms' measurements of (a) temperature, (b) humidity, and (c) CO_2 concentration. Fig. 7 illustrates the daily mean profile of the non-heating season for all the classrooms' measurements of (a) temperature, (b) humidity, and (c) CO_2. As seen in the figures, there were variations in the CO_2 concentration levels with respect to the monitoring period during both the heating and non-heating seasons. In the CO_2 concentration profiles (Figs. 6c and 7c) of the classrooms, the sharp decreases were due to the occupancy patterns (of each classroom) that varied during the weekdays, e.g., the students had sport lessons in the sports hall or painting lessons in the ceramic studio. Concerning the differences between the same ventilation modes of the two schools, the study differed from previous studies. According to the *t*-test results, there was no statistically significant difference in the CO_2 concentrations considering the school type and season ($p = 0.387$).

In the same ventilation mode for both schools' classrooms (TVC1, TVC4), where the measured ventilation mode was insufficient for IAQ comfort, the CO_2 concentrations exceeded the accepted limits for durations ranging from 110 min to 150 min, creating an unpleasant learning environment. However, the pairwise comparisons of ANOVA with TUKEY for both seasons showed that there were statistically significant differences between the traditional ventilation mode and natural ventilation mode (TVC1-NVC2, $F = 38.12$ $p = 0.001$, and TVC4-NVC5, $F = 56.12$, $p = 0.003$) and between the traditional ventilation mode and mechanical ventilation mode (TVC1-MVC3, $F = 72.01$ $p = 0.005$ and TVC4-MVC6, $F = 51.04$ $p = 0.000$) in each school. This finding highlighted the significance of different ventilation strategies to provide better IAQ. Considering the CO_2 concentration values in the mechanically ventilated classrooms, there were only slight differences between MVC3 and MVC6, which confirmed the positive contribution of the heat recovery unit during the teaching periods. This point demonstrates the crucial need for natural ventilation strategies combined with automatically activated systems when indoor CO_2 levels exceed the defined acceptable limits. Regarding the seasonal performance, the increased trend of opening windows in the non-heating season to the heating season influenced the sufficient fresh air intake of

Heating Season

(a)



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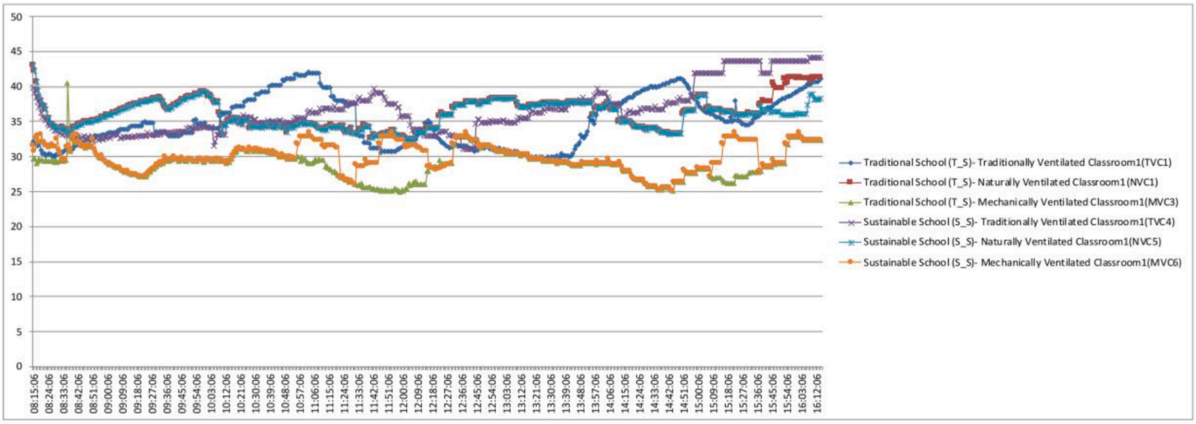

(c)

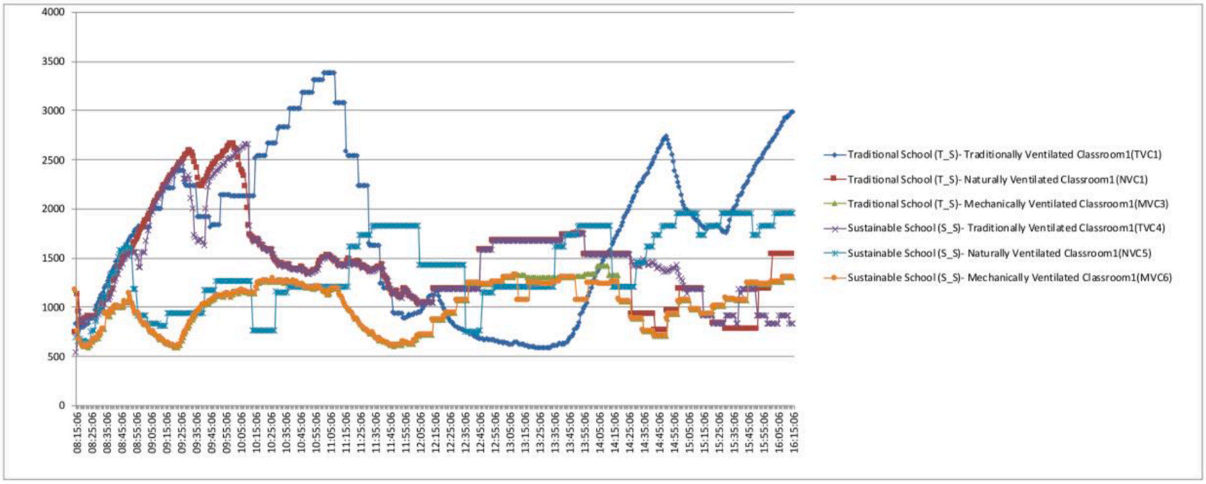

Fig. 6. Daily mean profile of heating season for classrooms' measurements of (a) temperature, (b) humidity, and (c) CO_2 concentration.

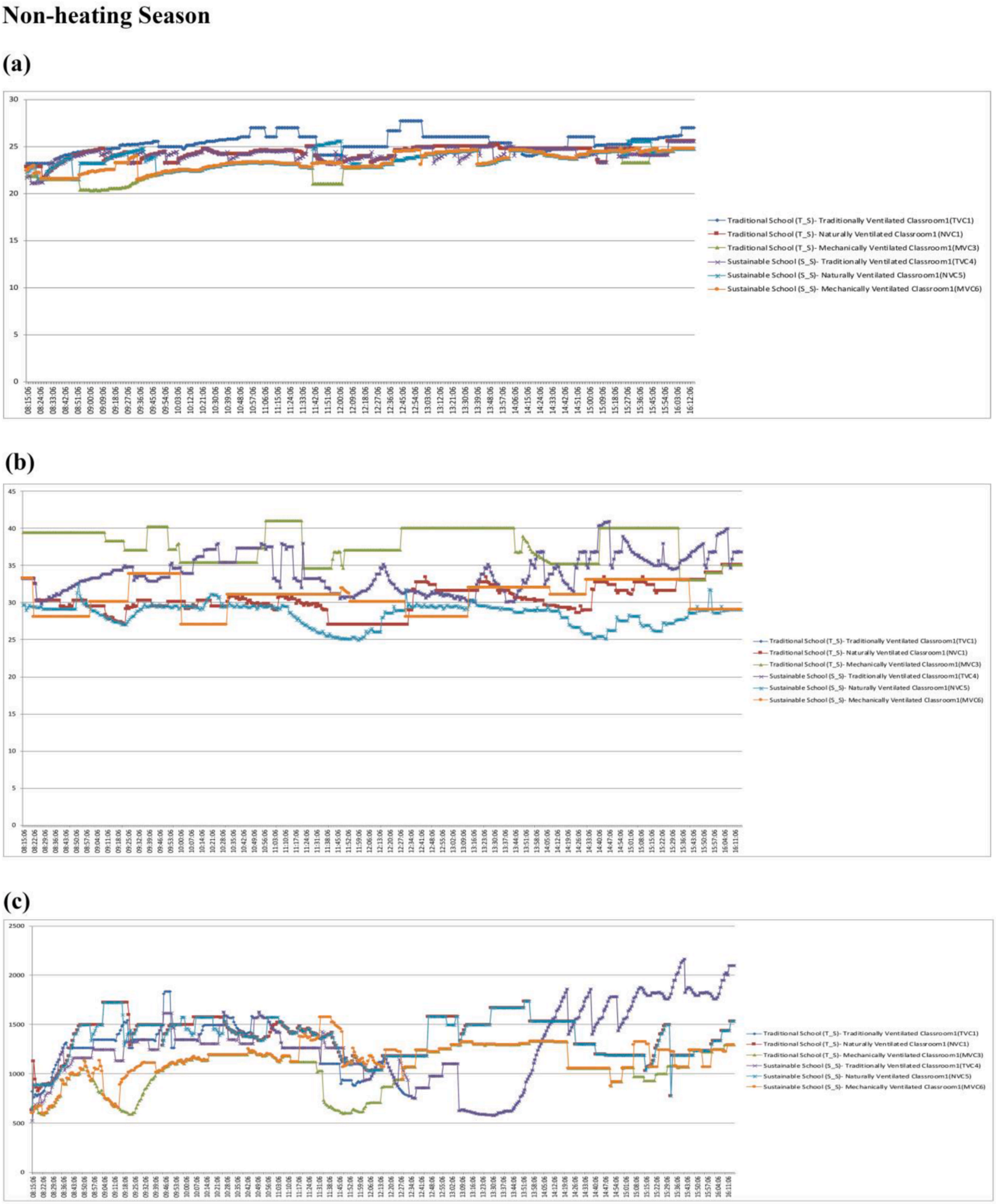

Fig. 7. Daily mean profile of non-heating season for classrooms' measurements of (a) temperature, (b) humidity, and (c) CO_2 concentration.

the classrooms during the occupied period during the non-heating season, so that TVC1, NVC2, TVC4, and NVC5 had higher levels of CO_2 concentration than they were in the non-heating season.

The study did not find any statistically significant differences in the temperature and humidity values between the two schools for natural and mechanical ventilation modes ($p = 0.124$). However, pairwise comparisons of the Wilcoxon Rank Sum test (with Bonferroni corrections) for both seasons showed that there were statistically significant temperature differences between the traditional ventilation mode and natural ventilation mode (TVC1-NVC2, $F = 101.09$ $p = 0.001$, and TVC4-NVC5, $F = 77.08$, $p = 0.000$) and between the traditional ventilation mode and mechanical ventilation mode (TVC1-MVC3, $F = 30.12$ $p = 0.002$, and TVC4-MVC6, $F = 17.89$, $p = 0.000$) in both seasons. Fig. 6a and b shows that the indoor temperatures of TVC1 and TVC4 increased during the heating season because of the radiators, the presence of the children during teaching hours (without any windows opened), and the outdoor temperature (in the non-heating season). However, the indoor temperatures of NVC2 and NVC5 in the non-heating season were also influenced by the long durations of open windows in summer, while the humidity decreased (Fig. 7a and b). This additional ventilation rate through the windows decreased the CO_2 concentration while increasing the indoor temperature of the classrooms, leading to discomfort.

Considering the three comfort parameters of IAQ, similar to the findings of Heracleous and Michael [12], this study also found that the indoor CO_2 level and outdoor temperature are the key determinants for the manual management of the ventilation modes of a classroom. Higher outdoor temperatures during the non-heating season allowed the windows to be opened as long as possible until the children felt acoustic and thermal discomfort. However, lower outdoor temperatures in the heating season (with windows rarely opened for long durations) led to poor indoor quality. Therefore, steeper fluctuations in the CO_2 concentration, temperature, and humidity variations were observed in the heating season compared to the non-heating season, with a similar pattern of occupancy.

4.2. *Cognitive performance*

Table 2 illustrates the percentages of children who did well in both the ST and SCT tests as indicators of their cognitive performances and the correlation coefficient for each scenario. From the p values, all the air quality parameters were statistically significant regardless of the scenario. The mean percentages were stratified by the ventilation mode, school type, season difference, and time of the monitoring period. As seen in Table 2, classrooms with the traditional ventilation mode (TVC1, TVC4) and natural ventilation mode (NVC2 and NVC5) had lower success percentages in the arithmetic attention compared to those obtained for the mechanical ventilation mode, regardless of the school type. However, the classrooms with the natural ventilation mode (NVC2, NVC5) had the lowest success percentages in visual attention, regardless of the school type.

The arithmetic attention success percentages in both the traditional and natural ventilation modes dropped significantly in the non-heating season compared to the percentages obtained in the heating season. This was probably due to the impact of the face-masks, along with the increase in the indoor temperature and the decrease in the humidity; we can deduce this because all the other variables were kept constant for the heating and non-heating seasons: the children were the same participants, classrooms were the same, and tests were the same (under the same exposure conditions). Similar to the studies, our study also found the highest cognitive performance of both attention levels in the mechanically ventilated mode of the sustainable school type; however, unlike the previous studies, there was no statistically significant difference in the cognitive performance of the children in the mechanical ventilation mode when the seasonal change was considered. This finding highlights the significance of further studies to test each attention performance independently under the same baseline CO_2 concentration exposure but with changing indoor temperatures and humidity levels.

To assess the impact of the three ventilation modes on the cognitive performance of the children, the visual and arithmetic test results were processed using ANOVA. The ANOVA results of each school showed a significant cognitive performance difference ($p = 0.000$) among the ventilation modes in both seasons. However, the further analysis of ANOVA with TUKEY Post Hoc comparisons during both seasons found that there was a statistically significant arithmetic attention difference between the traditional ventilation mode (TVC1-TVC4) and mechanical ventilation mode (MVC3-MVC6) and natural ventilation mode (NVC2-NVC5) and mechan-

Table 2
Percentages of successful children in both Stroop test (ST) and star counting test (SCT) tests as indicators of cognitive performance.

	Visual Attention Performance-ST Success Percentage						Arithmetic Attention Performance-SCT Success Percentage					
	H.			Non H.			H.			Non H.		
	Start	End	Coeff.	Start	End	Coeff.	Start	End	Coeff.	Start	End	Coeff.
Ventilation mode												
T_S												
TVC1	71.4 %	81.8%	0.501*	73.5%	79.2%	0.422*	19.5%	27.8%	0.305*	9.5%	12.8%	0.284*
NVC2	61.7%	75.8%	0.785*	62%	70%	0.581*	19%	23.3%	0.696*	13.4%	15%	0.405*
MVC3	67.9%	81.7%	0.700*	68.8%	96%	0.321*	42.9%	49.1%	0.303*	48%	51%	0.253*
S_S												
TVC4	70.8%	80.9%	0.405*	75%	78%	0.384*	12.5%	19.2%	0.301*	7.3%	11%	0.123*
NVC5	73.7%	77%	0.582*	71%	74.4%	0.463*	22.2%	27.3%	0.204*	18%	20.2%	0.362*
MVC6	79.7%	88%	0.321*	82%	95%	0.102*	49.7%	51.5%	0.617*	55%	62.3%	0.100*

Note: H is the heating season; Non H is the non-heating season; StDev is standard deviations; Coeff is the correlation coefficient.
$^*p < 0.05$.

ical ventilation mode (MVC3-MVC6). Still, there is no statistically significant visual attention difference between the traditional ventilation mode (TVC1-TVC4, $F = 121.09$ $p = 0.247$) and natural ventilation mode (NVC2-NVC5, $p = 0.179$) during both seasons. The *t*-test data on both visual attention and arithmetic attention data revealed that the school type did not differ statistically ($p = 0.304$).

4.3. *Academic performance*

The teachers of all the classrooms provided the data of the qualitative and quantitative scores of 120 children. The results obtained from the tests of each student were expressed in percentages. Table 3 illustrates the mean percentages of the children's qualitative and quantitative performance scores concerning the ventilation mode and season and the correlation coefficient for each scenario. From the p-values of correlation coefficients, academic performance in the different ventilation modes was only statistically significant in the non-heating season regardless of the school. The ANOVA results showed that there was no statistically significant difference in the qualitative or quantitative performance scores among the ventilation modes during the heating season; however, in the non-heating season, there was a statistically significant difference in both the qualitative and quantitative performance scores among the ventilation modes ($p = 0.000$) Further analysis of ANOVA with TUKEY Post Hoc comparisons showed that the traditional ventilation mode differed significantly from both the natural and mechanical ventilation modes regardless of the school type ($p = 0.000$).

Although the CO_2 concentration levels in the traditional mode (TVC1, TVC4) were higher during the heating season, the statistical difference between the traditional mode classrooms (TVC1, TVC4) and the other mode classrooms (NVC2, MVC3, NVC5, MVC6) was higher in the non-heating season than the heating season. Table 3 shows a greater decrease in the performance percentages of the children's qualitative and quantitative scores in TVC1 and TVC4. Thus, it was further identified that other conditions, such as wearing a facemask, significantly affected academic performance besides the poor IAQ and CO_2 concentrations being above the acceptable limits. This finding indicates the significance of improved ventilation modes during pandemic situations, where the occupants wear facemasks. According to the attendance data recorded by the teachers, the study found a statistically significant relationship between the absence rate and implemented ventilation mode. In the mechanically ventilated mode of both schools in both seasons, the number of absent children (due to upper respiratory tract infections) was less than that in other ventilation modes. This finding is also in line with previous studies that have tested and determined strong associations between human health and IAQ.

4.4. *Perceived indoor quality*

The children's mean responses to the perceived IAQ are summarized in Table 4. Table 4 illustrates the detailed response distribution of temperature, air moisture, and CO_2 concentration-level perception using a 7-point scale for rating during both the heating and non-heating seasons. In the heating season, in TVC1, the percentage of children with the “slightly warm” perception was higher (67 %), followed by 25 % with the “neutral” perception. In contrast, in the same season, the percentage of children in TVC4 that perceived the room as “hot” was 53.8 %, followed by 28.2 % of students perceiving the room as “slightly warm.” None of the children considered the “cold” thermal perception. These differences between the two schools of the same ventilation mode pointed out the impact of air tightness and sustainability characteristics of the sustainable school on the temperature perception of the children. In the non-heating season, in both schools, the children in TVC1, NVC2, TVC4, and NVC5 with the “hot” perception were a higher percentage (67.3 %). However, in MVC3 and MVC6, the children with “neutral” perceptions were a higher percentage (78 %). In both schools, in both seasons, female participants felt the temperature discomfort more than the male participants by stating that “they wish it were a bit colder.” As seen in the table, the predicted mean vote (PMV) index had mean values of 2.05 and 2+-0.15 in the traditional and natural ventilation mode, respectively, for both the schools during the non-heating season, which is considered to be inadequate for category C in the EN ISO 7730 standard [41].

During the heating season, the percentage of children in TVC1 and TVC4 with the “slightly dry” perception was higher at 55 %, followed by 28 % for the “dry” perception. However, in the non-heating season, in both schools (regardless of the ventilation type), the majority of the children (70 %) rated the air moisture as “humid,” although the measurement results measured the humidity as 40 % maximum. In both seasons, in the natural and mechanical ventilation modes of the two schools, the majority of the children (69 %)

Table 3
Mean percentages of qualitative and quantitative performance scores regarding ventilation mode and season.

	Qualitative Success Percentage						Quantitative Success Percentage					
	H.			Non H.			H.			Non H.		
	Start	End	Coeff.	Start	End	Coeff.	Start	End	Coeff.	Start	End	Coeff.
Ventilation mode												
T_S												
TVC1	76.2 %	69.4%	**0.001**	73.5%	59.2%	0.301*	88.5%	74.3%	0.003	89.5%	52.8%	0.400*
NVC2	80.9%	81.9%	0.005	82%	83.2%	0.509*	86%	85.1%	0.001	83.4%	85%	0.302*
MVC3	81.8%	83.1%	0.002	82.5%	83%	0.536*	86.7%	85.2%	0.006	88%	91%	0.241*
S_S												
TVC4	77.8%	80.9%	0.014	75%	58%	0.570*	72.5%	69.2%	0.015	77.3%	61%	0.003
NVC5	78.7%	79%	0.002	73%	74.4%	0.202*	72.2%	77.3%	0.001	78%	80.2%	0.612*
MVC6	80.7%	85%	0.006	82%	85%	0.333*	79.7%	81.5%	0.008	85%	87.3%	0.362*

Note: H is the heating season; Non H is the non-heating season; StDev is standard deviations; Coeff is correlation coefficient.
*$p < 0.05$.

Table 4
Detailed response distribution of temperature, air moisture, and CO_2 perception.

Perceived indoor air quality ratings

Temperature	Cold (−3)		Cool (−2)		Slightly cool (−1)		Neutral (0)		Slightly warm (1)		Warm (2)		Hot (3)		Total		PMV	
	H.	Non-H.	H.	Non-H.	H.	Non-H.	H.	Non-H.	H.	Non-H.	H.	Non-H.	H.	Non-H.	H.	Non-H.	H.	Non-H.
Ventilation mode																		
T_S																		
TVC1	0	0	0	0	0	0	5	5	14	2	1	0	0	13	20	20	0.8	2.05
NVC2	0	0	0	0	0	0	8	5	10	0	2	2	0	13	20	20	0.7	2.15
MVC3	0	0	0	0	5	2	12	15	3	3	0	0	0	0	20	20	−0.1	0.05
S_S																		
TVC4	0	0	0	0	0	0	3	2	6	4	0	3	11	13	20	20	1.95	2.25
NVC5	0	0	0	0	0	0	8	5	10	0	2	2	0	13	20	20	0.7	2.1
MVC6	0	0	0	0	5	1	1	15	1	2	2	0	0	0	20	20	0	0.05

Air Moisture	Very humid (−3)		Humid (-2)		Slightly humid (−1)		Neutral (0)		Slightly dry (1)		Dry (2)		Very dry (3)		Total	
	H.	Non-H.	H.	Non-H.	H.	Non-H.	H.	Non-H.	H.	Non-H.	H.	Non-H.	H.	Non-H.	H.	Non-H.
Ventilation mode																
T_S																
TVC1	0	0	0	0	0	8	4	0	11	12	5	0	0	0	20	20
NVC2	0	0	0	6	0	7	14	4	3	3	3	0	0	0	20	20
MVC3	0	0	0	7	5	4	10	8	5	1	0	0	0	0	20	20
S_S																
TVC4	0	0	0	8	5	5	10	7	11	0	5	0	0	0	20	20
NVC5	0	0	0	7	7	6	13	7	0	0	0	0	0	0	20	20
MVC6	0	0	0	8	4	5	12	7	3	0	1	0	0	0	20	20

Air Freshness	Very stale (−3)		Stale (−2)		Slightly stale (−1)		Neutral (0)		Slightly Fresh (1)		Fresh (2)		Very fresh (3)		Total	
	H.	Non-H.	H.	Non-H.	H.	Non-H.	H.	Non-H.	H.	Non-H.	H.	Non-H.	H.	Non-H.	H.	Non-H.
Ventilation mode																
T_S																
TVC1	0	0	12	10	4	5	4	5	0	0	0	0	0	0	20	20
NVC2	0	0	0	0	6	7	14	13	0	0	0	0	0	0	20	20
MVC3	0	0	1	0	5	6	13	13	2	1	0	0	0	0	20	20
S_S																
TVC4	0	0	13	8	5	10	2	2	0	0	0	0	0	0	20	20
NVC5	0	0	0	0	6	3	14	13	0	4	0	0	0	0	20	20
MVC6	0	0	0	0	4	3	13	13	3	4	3	0	0	0	20	20

rated air freshness as “neutral; ” none of the children rated it “stale.” However, during the heating season, the percentage of children in the traditional ventilation mode in both schools having the “stale” perception was higher (66 %). These perceptions showed that in the non-heating season, the children (wearing facemasks) in typical school buildings were more sensitive to temperature variations than the CO_2 concentration and humidity variations compared to those in sustainable school buildings.

5. Conclusion

Primary schools are critical environments where ventilation modes vary from purposefully designed mechanical systems to manually opening windows and doors. This results in poor IAQ decreased performance and a high risk of viral airborne transmission among children. Thus, many studies have suggested heating, ventilation, and air-conditioning (HVAC) strategies to increase ventilation in occupied zones. However, there are many other parameters, such as local conditions, seasonal differences, building characteristics, and class sizes, that should be compared and monitored case by case in real-occupied classroom environments during real learning activities. Our study reviewed 455 Turkish schools and experimentally assessed the effects of different ventilation modes on the air quality parameters and cognitive and academic performances of primary school children studying in two representative school buildings with varying construction characteristics during heating and non-heating seasons. The non-heating season of the study was conducted during the COVID-19 pandemic.

To the best of the author's knowledge, this study is the first experimental study in which the children were wearing facemasks during the monitoring periods in a real pandemic situation; this helped us to compare the effects of different ventilation modes in real primary school classrooms on reducing viral airborne transmission, while simultaneously analyzing the role of proper ventilation in enhancing the academic and cognitive performance of the children. Although the significance of viral transmission via aerosols during the COVID-19 pandemic has been discussed intensively by researchers [42,43], there is still uncertainty regarding the benefits of an effective ventilation system in closed spaces. Thus, to support these findings, further studies are needed to monitor IAQ with more accurate control of different levels of CO_2 exposure and use brain-imaging techniques to understand better the cognitive impacts of wearing facemasks under different CO_2 exposure conditions. Future studies are recommended to independently investigate the associations between CO_2 concentration levels, performance, and perceived comfort by testing different temperature levels under a maintained level of CO_2 concentration. Moreover, the changing levels of CO_2 concentration could change the children's window control behavior, which could be investigated in a future study.

Following the above considerations, our findings highlight that the CO_2 concentration levels were higher than the accepted limits several times, even immediately after 20 min of the occupied period, because of the lack of proper ventilation systems. Compared to the sustainably built schools, the worse scenario was monitored in traditional schools, which were constructed without considering energy efficiency regulations and green design principles. However, the sustainability characteristics of the buildings were not adequate to control the CO_2 concentration levels efficiently. While many studies have focused on decreasing the occupation rate and implementing new furniture layouts in occupied zones to control and limit the spread of airborne virus-carrying particles, there is an inevitable need to supplement the existing ventilation systems with other mechanisms to provide fresh air to the classrooms. As demonstrated in the study, the heating season is more critical than the non-heating season, which should be treated differently when studying CO_2 concentrations and their impacts. Our study showed significant seasonal variations with respect to the cognitive performances of the students in the traditional and natural ventilation modes, but with respect to academic performances, significant variations were observed only in the traditional ventilation mode. The seasonal variations were not significant for the mechanical ventilation mode concerning the children's cognitive and academic performances. There were also significant seasonal variations concerning the perceived IAQ. Concerning the higher CO_2 concentration levels, the arithmetic attention success percentages of the children were impacted more than their visual attention success percentages. This finding could be validated by analyzing the speed performances of the children in more occupied schools. The subjective findings of the study highlight that the perceived temperature appeared to be linked more dominantly to the indoor comfort conditions than the perceived air freshness.

As with all studies, this study also has limitations. The experiments were conducted in real classrooms, which could be a disadvantage in controlling other cognitive responses caused by other environmental factors during the monitoring periods. The natural ventilation mode was considered only by opening operable windows and doors, but there could be different results with different window-opening patterns and natural ventilation strategies.

Author statement

Yasemin Afacan: Conceptualization; Literature review; Data curation; Data analysis; Funding acquisition; Investigation; Methodology; Supervision; Validation; Visualization; Roles/Writing - original draft; Writing - review & editing.

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Declaration of competing interest

The author declared 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

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