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Classroom airing behaviour significantly affects pupil well-being and concentration performance – Results of a large-scale citizen science study in Danish schools

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A B S T R A C T

This study surveyed the indoor environment in Danish classrooms and explored its associations with pupil well-being and performance. It was a large-scale citizen science study using a simple intervention carried out over two days. On one of these days, the participating classes carefully aired out the classroom during the break before a lesson dedicated to measuring the classroom environment. They did this by keeping windows open and leaving the classroom during the break. On the other day, they were told to do as they usually do, i.e. they received no instruction to follow a particular airing behaviour. The order of the two airing behaviours was randomly balanced between classes. Measurements were reported by 709 classes in 234 schools and 640 classes completed a building checklist. In total, 21,326 well-being surveys and 20,701 concentration tests were completed by the pupils. Of these, a gross subsample of 13,094 records qualified for further analysis. With the instructed airing behaviour, the percentage of classes with a CO_2 concentration higher than 1000 ppm was reduced from 53% to 36% as compared with uninstructed behaviour. This finding corresponded with earlier related studies carried out in Danish classrooms in 2014 and 2009. Airing also improved the pupils' perception of the classroom environment, alleviated their building-related symptoms and increased their performance of a concentration test in which they made 6% fewer errors than with uninstructed behaviour. Based on responses from a large number of pupils, the findings confirm that inadequate classroom ventilation negatively affects pupil well-being and concentration and that classroom air quality continues to present a challenge in many Danish school buildings.

1. Introduction

An increasing number of studies suggests that the classroom environment adversely affects pupils' cognitive processes and mental performance [50,39,14,26,6,53], perceived symptoms [7,39,34,5,1,41], absenteeism ([24,29,44], and general well-being [29,7]. Also, classroom characteristics, such as type of ventilation, have been associated with pupils' satisfaction with the indoor environment and their learning outcome [8,47]. Despite these findings documenting that the classroom environment is important for pupil learning and well-being, upgrading school buildings and their installations seems to happen slowly. Reasons include inadequate financial resources for upgrading ageing school buildings and an emphasis on energy conservation [11]. Yet, several studies have documented the massive economic benefits of investing in a better indoor environment in schools and other building types [21,45,49]. Continued studies on the detrimental effects of the poor indoor environment on pupils, particularly on the benefits achieved by upgrading school buildings, may incentivise decision-makers to prioritise the needed investment.

For more than a decade, several large-scale surveys have recorded and documented the indoor environment in Danish classrooms. In 2009, Menå and Larsen [36] found that the CO_2 concentration during winter was higher than 1000 ppm in more than 50% of 743 classrooms across the country. The pupils themselves performed point-in-time measurements of the CO_2 concentration and temperature at the end of a lesson during which they kept the windows closed to mimic a typical Scandinavian heating season scenario. Using a similar approach in an even higher number of classrooms (785), Clausen et al. [12] obtained nearly the same outcome, suggesting no noticeable improvement in classroom air quality during the intervening time. Shortly after, a follow-up study using a different procedure with continuous, weeklong mea-

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surements showed that in 91% of the 245 surveyed classrooms, the CO_2 concentration exceeded 1000 ppm at least some time during the school day [13]. On average, the CO_2 concentration in these classrooms exceeded 1000 ppm during 45% and 12% of the school day during the heating and cooling seasons, respectively. In 2021, a comprehensive study was again conducted in Danish classrooms, but this time featuring the recording of pupil perceptions of their classroom environment, building-related symptoms and concentration performance, along with the measurement of thermal, air quality, and visual and acoustic conditions in the classrooms. This paper reports the findings of this recent study.

2. Methods

In Denmark, a large-scale citizen science study is organised each year by the National Centre for Science Education under the Danish Ministry of Children and Education, Astra (https://www.astra.dk). The annual studies intend to promote the natural sciences among pupils from primary to high school. In 2021, the focus was on the indoor environment in classrooms, and the event followed up on and was inspired by the earlier similar studies in 2009 and 2014. Classes across the country were invited to take part in the project through advertisement among science teachers and promotion through the ''Big Bang'' conference, a conference held annually in Denmark for science teachers. The study was initially planned to be carried out in October 2020 but was postponed to November 2021 since classes were frequently sent home in the autumn of 2020 due to the Covid-19 pandemic.

2.1. Experimental design

On two days in two successive weeks, the participating classes followed two different behaviour patterns labelled ''airing behaviour'' and ''uninstructed behaviour''. Each of these behaviour patterns is described in the following.

2.1.1. Airing behaviour

1) Classes were instructed to leave their classrooms during the break before the lesson when measurements were made.
2) During the break, the classrooms were unoccupied, and windows were kept open to ventilate the rooms as efficiently as possible.
3) After returning from the break, windows were closed and remained closed during the entire lesson when the measurements were made.

2.1.2. Uninstructed behaviour

No particular behaviour was instructed, meaning that the classrooms could be anywhere from unoccupied to fully occupied during the break before the lesson when measurements were made. Also, the state of the windows was uninstructed, and classes could open or close windows and doors as they desired, but only during the break. This behaviour pattern was chosen because it represents a typical Scandinavian winter scenario. Windows remained closed during the entire lesson when the measurements were made.

The order of the two behaviour patterns was randomly balanced between classes leading to a cross-over experimental design.

Classes could decide when to carry out their measurements during the period from 1 November to 10 December 2021 (weeks 44 to 49).

2.2. Study components

The study activities comprised four components:

1. Measurement of physical indoor environment parameters in the classroom (completed at class level).
2. A here-and-now, online survey of pupil perceptions of the indoor environment in their classroom and their building-related symptoms (completed at pupil level).
3. An online task to measure pupil concentration performance (completed at pupil level).
4. Description of the classrooms and building installations (completed at class level).

1. to 3. were completed on both experiment days, while 4. was completed only once, typically on the first experiment day. Classes received unique links to online data entry forms and a class id to link them with their data. For the pupil level input, teachers assigned a unique number to each pupil that was combined with class and school id's.

Prior to the measurements, all classes received a measurement kit containing equipment to measure the CO_2 concentration and globe- and air temperatures. Measurement of illumination and acoustical parameters were made with apps on mobile phones. The selection of appropriate apps and careful testing of their performance were handled in pilot studies in both lab and field settings before deciding on the final methodology. As described in section 2.3, all measurements were instantaneous and short-term, except the measurement of sound pressure level, which was done during an entire lesson. Measurements were made by the pupils assisted by their teachers, and instruction videos and detailed written manuals were prepared for both teachers and pupils to support their completion of the study. In a step-by-step manner, the manuals described how to do the measurements and provided background information and guideline values for the classes to compare with.

2.3. Measurements

2.3.1. Physical parameters

2.3.1.1. CO_2-concentration. Instantaneous measurement of the CO_2 concentration was made with a Kitagawa 126SF measuring tube connected to a syringe via a rubber tube. During 1 min, 50 ml of air was pulled through the tube, and then the reading was done directly on a scale on the tube. The reading was subsequently multiplied by 2 to adjust for a lower air volume than the nominal 100 ml. With this way of measuring, the upper limit of the measurement range was 4000 ppm. The manufacturer specified the relative standard deviation of the measurement as 10% of the reading. The median number of pupils occupying the classrooms was 19. With pupils moving and releasing convective heat, good mixing of the air throughout the occupied zone of the classrooms was assumed.

2.3.1.2. Temperature. Instantaneous measurement of both globe- and air temperatures were done. An adhesive temperature strip (resolution 2 °C) was attached to a ping-pong ball with a diameter of around 40 mm. The ping-pong ball was mounted on a 30 cm long wooden skewer (barbecue skewer). By waving the skewer and moving the ping-pong ball through the air for 30 s, the temperature strip measured the air temperature. Globe temperature was measured when the skewer was fixed to a chair, preferably at 0.6 m height and located in the middle of the classroom.

2.3.1.3. Illuminance. Instantaneous measurement of the classroom illuminance was made with mobile phones with the app ''Ljus'' [2]. This app is available only for iPhones. For specific models of this brand, the developer calibrated the app to daylight at 100% cloudiness and to artificial light with a fluorescent lamp at a correlated colour temperature of 2800 K. The developer indicates that the sensitivity of the mobile phone camera deviates between types of daylight and light sources but does not specify the magnitude of the deviation. Tests carried out before deciding which app to use showed a deviation between the app and a reference instrument (Extech light meter) of up to 15% at illuminances up to 1100 lx (deviation increasing with illumination).

The classrooms were divided into four equally sized fields, and the measurement was made in the centre of each field. The classes repeated the lighting measurement under four different conditions: A) Lighting on, no solar shading; B) Lighting off, no solar shading; C) Lighting on, solar shading in use; D) Lighting off, solar shading in use.

The mean value of the illuminances measured in the four fields represented different lighting states. A rule was therefore set up to pick out which one of these four values would be the most relevant to explore the association between the classroom illumination and the pupils' subjective responses. The rule was based on the reported values of two other questionnaire items regarding solar radiation and solar shading position. It was assumed that the artificial lighting was off if the sun shone. The classroom mean illumination was calculated for each of the following conditions, and one of these values was then used as the independent variable based on the reported solar radiation and use of solar shading:

No sun, no solar shading -> illumination measured under condition A).

Sun, no solar shading -> illumination measured under condition B).

No sun, solar shading -> illumination measured under condition C).

Sun, solar shading -> illumination measured under condition D).

2.3.1.4. Sound pressure level. The sound pressure level was recorded with mobile phones with the app "Noise exposure"[3]. The developer made recordings with a wide range of mobile phones and compared these with a reference instrument. This test concluded that the app worked well for sound pressure levels between 40 and 100 dB_A, but that sound levels dominated by frequencies below 200 Hz could be underestimated. Children's fundamental frequency (voice pitch) lies around 300 Hz, for women around 200–240 Hz, and for men around 100–120 Hz [40,18]. Initial testing by comparison with a reference instrument (PeakTech 8005) indicated that the result depended on the applied mobile phone but that the deviation between the reference instrument and the app for the tested phones (OnePlus 6 T, iPhone 6 and 11) was <7% in the range up to 70 dB_A. In the classes, measurements were made near the blackboard with the microphone facing the classroom. The logging interval was 1 s, and classes reported an average of the recordings made during the lesson (around 45 min).

2.3.2. Here-and-now survey of pupil perceptions and symptoms

A short online questionnaire queried pupils about their perception of different indoor environment factors and the intensity of selected symptoms. To be applicable across all class grades, the questionnaire used emojis to indicate the degree of annoyance with adverse perceptions (e.g. being cold) or the intensity of symptoms. All scales used five categories ranging from No annoyance/symptom to Strong annoyance/symptom, as shown in Fig. 1 for the perception of the classroom temperature and the intensity of headache.

The questionnaire used illustrations to aid pupils in responding more easily by providing images familiar to children's feelings and past experiences. Using words only may fail to describe the exactness of the subjective experience [25]. Also, scales usually used in a bi-polar format, e.g. ranging from cold to warm, were split into two unipolar scales. For thermal sensation, these would then go from not too warm to too warm or from not too cold to too cold as shown in Fig. 1. The reason for this modification is that earlier studies have shown that children below 4–5 grade (10–11 years old) find it difficult to relate to bipolar scales [48]. Seven five-point scales queried the pupils about their perception of cold, warm, draught, air quality, noise, light, and dark, and five five-point scales quantified the intensity of tired eyes, headache, lethargy, concentration performance, and willingness to work.

2.3.3. Concentration performance

The pupils completed a small online test to assess their concentration performance on both experiment days. The test was based on the Baddeley test, which involves higher mental processing and has been shown to be sensitive to environmental stresses [4]. This test was chosen because it is short and easy to administer and could therefore be adapted to online use. Also, the test is considered to be sensitive with an only modest practice effect. The risk of bias due to practice was also accounted for by balancing classes by the order of the uninstructed and airing behaviours. In the original Baddeley test, subjects are asked to categorise statements on the order of two letters. To adapt the test to children, the original grammatical-logical test was replaced by a graphical-logical test. The pupils should then mark if a statement concerning the relation between two geometrical figures was true or false. Fig. 2 shows an example of the graphical-logical test.

Altogether, the pupils were presented with 24 such statements on each experiment day. Total items correct has generally proved the most sensitive score [4]. In the analyses of the pupils' responses to the test, the number of correct answers was transformed to the number of incorrect answers (24 – correct) as the number of incorrect answers followed a negative binomial distribution for which consolidated analysis methods were available.

2.3.4. Building checklist

To complete the building checklist, pupils, together with their teacher, measured the area and the volume of the classroom and its window area. The checklist also described the main window orientation, light sources, building age, if the building had been refurbished within the past ten years, if pupils perceived any unpleasant smells when they arrived in the classroom in the morning, airing habits, type of natural ventilation (single-sided or cross-flow), type of ventilation system (mechanical with supply and exhaust, exhaust only or a mechanical system that was not running), outdoor surroundings and information regarding potential changes to the airing behaviour after onset of the Covid-19 pandemic. If changes to the airing behaviour were confirmed, a follow-up question asked which changes.

2.4. Data processing

The raw data was structured according to the four components of the study. First, individual datasets were scrutinised. On some occasions, classes or pupils submitted duplicate records. Most of these were identical, but as a general rule, the most recent record was kept. Mismatching class identity codes were sorted out (they should be identical for the building checklist, measurements, questionnaires and concentration performance test). Then for each component, variable values were manually inspected to exclude or correct obviously erroneous values (e.g. extreme window or classroom areas, records with a comma instead of a period as decimal separator, inputs containing characters instead of numerals or numbers containing characters, such as the Danish character "ø" instead of 0). A few classes reported ranges for the measured physical values (e.g. temperature 19–20). In these cases, the interval was corrected to the mean value of the range. Concentration test records were deleted if they consisted of purely "True" or purely "False" decisions. After the initial screening and processing, data

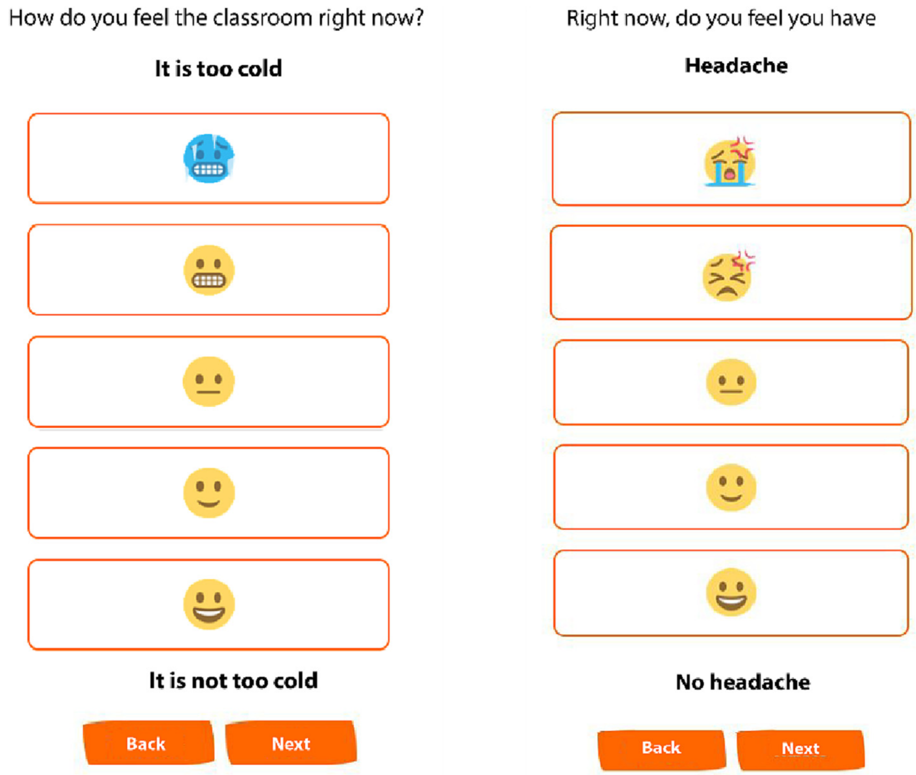

Fig. 1. Examples of the scales used to measure the pupils' perceptions of the classroom environment (left) and their symptom intensity (right).

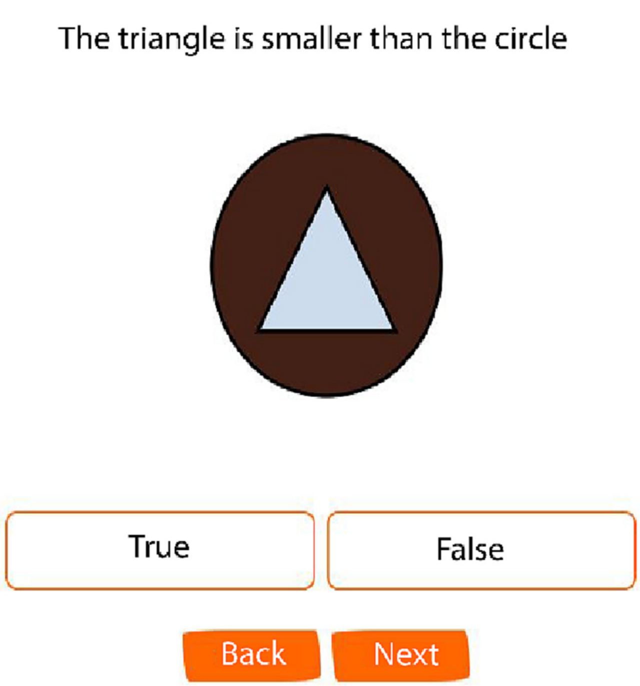

Fig. 2. Example of the graphical-logical concentration test.

sets were merged according to the class id and the experimental condition (airing or uninstructed behaviour).

It complicated the initial data processing that not all classes completed all study components on both designated experiment days. Also, some classes made measurements on one day and then recorded them in the online forms on a subsequent day. In the first case, classes with missing data were excluded from the analyses. In the second case, the merging of datasets was based on the dates when the different components were saved. Data was merged if measurements of the classroom environment were made up to 24 hrs before or up to 48 hrs after the online survey or concentration test was received. Otherwise, subjective data was discarded, as it was considered not to represent appropriately the indoor environment exposure of the week. Fig. 3 gives an overview of the number of classes, schools and pupils who contributed data to the study and shows the progress of the data processing.

2.5. Participation

Measurements were reported by 709 classes in 234 schools, and 640 classes completed the building checklist. A total of 21,326 well-being surveys and 20,701 concentration tests were received. Not all classes made measurements or completed the checklist, so a gross subsample of 13,094 records ultimately qualified for further analyses.

Table 1 presents the characteristics of the gross subsample of 13,094 records and the basic properties of the corresponding participating schools after processing the raw data and merging measurements, checklist observations, well-being surveys and concentration test responses. Table 1 shows data for this subsample based on the number of classes and pupils. Generally, the percentage distributions for classes and pupils matched well. In particular, the number of responses with both airing behaviours was of comparable magnitude.

2.6. Outdoor conditions during the study period

The study was carried out well into the heating season, which in Denmark starts on the 1 October. Outdoor data was recorded with

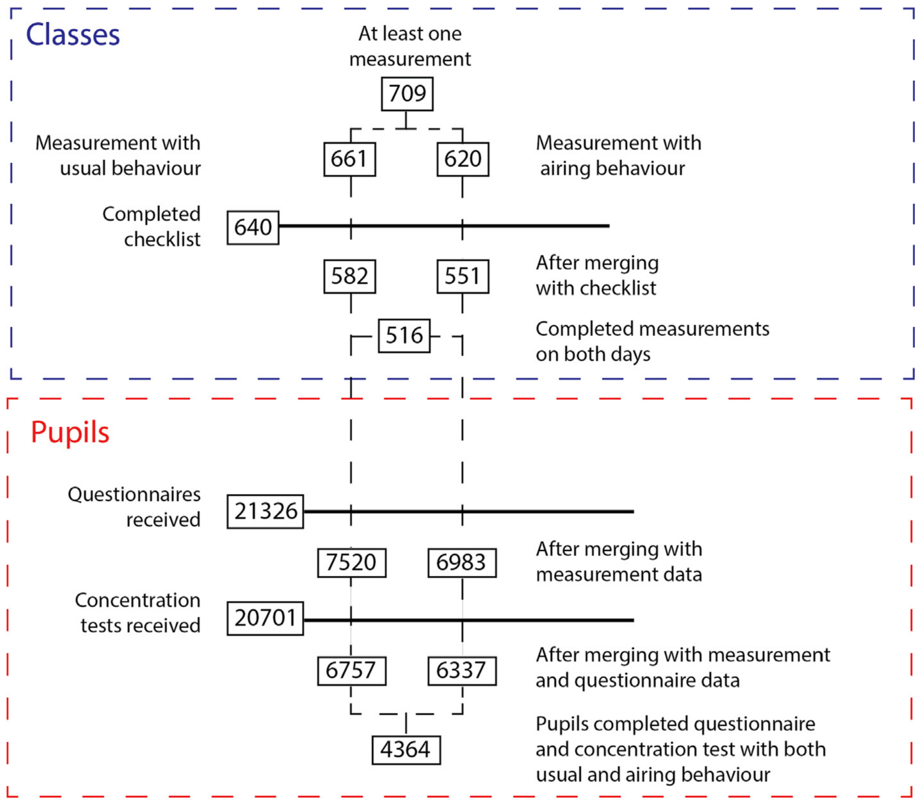

Fig. 3. Flow chart showing the number of classes completing the measurements and checklist and the number of pupils completing questionnaires and concentration tests.

a weather station located at the Technical University of Denmark just north of Copenhagen. Although the measurement location may not be representative of the microclimate near all the participating schools due to the modest size of Denmark, it may still indicate overall trends in the outdoor climate. Table 2 shows outdoor air temperatures and humidities aggregated for the study period on Mondays to Fridays from 8 am to 3 pm. Denmark is classified as warm temperate, fully humid, and warm summer (Cfb) according to the Köppen-Geiger climate classification.

2.7. Ethical considerations

Astra handled the ethical issues related to the study, but as no sensitive personal information or personally identifiable information was collected, no ethical approval by an ethics board was required.

2.8. Data analysis

Linear regression (LR) was used to evaluate the association between the logarithm of the outdoor illumination and the indoor illumination under the four lighting conditions. Generalised Linear Modelling (GLM) was used to assess the association between the logarithm of the measured CO_2 concentration and the ventilation type, class grade, volume per person and airing behaviour. QQ-plots were used to confirm the normality of the residuals after running the LR and the GLM analyses. A nonparametric equality-of-medians test was used to compare noise levels between classes with different types of ventilation.

The questionnaire responses were ordinal at five levels. As such, ordered logistic regression was used to analyse how questionnaire responses were associated with the airing behaviour, ventilation type and the measured physical parameters. Analyses were adjusted for gender and class grade. A Brant test was used to identify the independent variables that violated the assumption of proportionality of the odds of the ordinal logistic regression model. When this was the case, partially constrained generalised ordinal logistic regression was used to account for the variables that did not meet the proportional odds assumption at a 0.025 significance level [57,56,32]. In both proportional odds and partial proportional odds logistic regression analyses, standard errors were adjusted to allow for intragroup correlation (pupil within class) to relax the requirement that the observations be independent.

The outcome of the concentration test was an error count that could vary from 0 to 24. Associations between the error count and the airing behaviour, ventilation type and the measured physical parameters were analysed in mixed-effects negative binomial regression models with random components at two levels: class and pupil within class. The effect on the error count of the airing behaviour was evaluated in successive analyses to assess the robustness of the model outcomes: 1) An unadjusted, crude model with airing behaviour as the only independent variable; 2) as 1) with adjustment for gender and class grade; 3) as 2) with adjustment also for ventilation type; 4) as 3) with adjustment also for the measured CO_2-concentration; 5–7) as 4) with successive adjustment for the measured air temperature, noise level, and illumination. All models used an exchangeable covariance structure to account for the intra-subject correlation.

Increasing complexity of the applied models required an increasing number of independent variables to have non-missing values. Since not all classes recorded all the variables on both designated experiment days, the number of valid records decreased with increasing model complexity. Therefore, the number of observations used in the different models varied from 11106 to 12270.

All analyses were carried out with Stata IC version 17.0 (StataCorp, TX, USA).

Table 1
Basic characteristics of the study population and the participating schools.

Characteristic	Distribution of responses No. classes (% of classes) / No. pupils (% of pupils)
Class grade	
- Lower elementary	33 (5.1) / 546 (4.2)
- Middle elementary	268 (41.9) / 5271 (40.3)
- Higher elementary	309 (48.3) / 6761 (51.6)
- High school	23 (3.6) / 463 (3.5)
- Other	7 (1.1) / 53 (0.4)
Gender	
- Girls	–/ 6171 (47.1)
- Boys	–/ 6449 (49.3)
Not indicated	–/ 474 (3.6)
Airing behaviour	
- Uninstructed	582 (51.4) / 6757 (51.6)
- Airing	551 (48.6) / 6337 (48.4)
Ventilation type	
Natural	175 (27.3) / 3525 (26.9)
System not running	89 (13.9) / 1674 (12.8)
Exhaust only	133 (20.8) / 2723 (20.8)
Balanced mechanical	243 (38) / 5172 (39.5)
Age of school building	
- <1900	22 (3.5)
- 1900–1940	77 (12)
- 1941–1960	85 (13.3)
- 1961–1970	151 (23.6)
- 1971–1980	123 (19.2)
- 1981–1990	45 (7)
- 1991–2000	46 (7.2)
- 2001–2010	55 (8.6)
- 2011-	36 (5.6)
Volume per person	
- < 6 m^3	26 (4.6)
- 6–10 m^3	300 (53.6)
- 10–15 m^3	179 (32)
- 15–20 m^3	31 (5.5)
- greater than 20 m^3	24 (4.3)
Window-to-floor area ratio [1)]	
- < 0.1	61 (10.4)
- 0.1 – 0.2	259 (44.1)
- 0.2–0.3	208 (35.4)
- 0.3 – 0.4	52 (8.8)
- 0.4 – 0.5	8 (1.3)

[1)] Classes with window areas larger than 26 m^2 and floor areas larger than 90 m^2 corresponding to the 95% percentiles were considered outliers and therefore omitted from the calculated distribution of the window-to-floor area ratio.

Table 2
Outdoor air temperature and humidity aggregated for weekdays from 8 am to 3 pm for the study period.

	Mean	Minimum	Maximum
Air temperature (°C)	6.0	−1.1	12.5
Relative humidity (%)	78	54	91

3. Results

3.1. Measurements

Table 3 provides an aggregated summary of the measurements carried out with uninstructed and airing behaviours. In both scenarios, the median and mean CO_2 concentrations reached and exceeded the recommended value of 1000 ppm. With uninstructed behaviour, 53% of the classes measured a CO_2 concentration higher than 1000 ppm, while it was 36% with airing. This is well aligned with the corresponding results from the study in 2014. The majority of the measured temperatures (both air and globe) were in the interval of 20–24 °C as recommended for the heating season (EN 16798–2 2019). The measured temperatures reflect that all schools in Denmark have a heating system and that the study was conducted during the heating season. Table 3 shows only a modest difference between the air- and globe temperatures and that the airing behaviour resulted in an average temperature decrease of 0.6 to 0.8 °C compared with the uninstructed behaviour. The highest illumination was measured when the artificial lighting was on and with no solar shading. Across classes, median values were all lower than the 500 lx recommended for classrooms (DS/EN 12464–1 2021). The measurements were made in November and December when daylight in Denmark was limited (the measured average outdoor illumination was 5850 lx). Yet, the difference in illumination with the applied lighting scenarios was clear, with a trend as could be expected. Despite the relatively low outdoor illumination, there was a significant association between outdoor and indoor illumination, but it was strongest when the artificial lighting was off, and the solar shading was not in use (condition B) (LR, $p < 0.001$).

Many classes reported high sound pressure levels, which could be a natural consequence of the pupils' activities while conducting the measurements. The average sound pressure level in lower, middle and higher elementary school was 70 dB_A, while it was slightly lower at 68 dB_A in the high school classes. The sound pressure level was not associated with the type of ventilation (median test, p greater than 0.1).

Fig. 4 compares the CO_2 concentration measured with different ventilation types and uninstructed and airing behaviours. The median CO_2 concentration was higher in the classrooms with natural ventilation than in the classrooms with balanced mechanical ventilation or mechanical exhaust. The CO_2 concentration depended significantly on the ventilation type (GLM, $p < 0.001$) and the airing behaviour (GLM, $p < 0.001$). In classrooms with volumes of more than 10 m^3 per capita, the CO_2 concentration decreased significantly with the increase of per capita volume (GLM, $p < 0.001$). The interaction between airing behaviour and type of ventilation showed that the effect on the CO_2 concentration of airing the classroom was significantly smaller with balanced mechanical ventilation than with natural or exhaust ventilation or when the ventilation system was off (GLM, $p < 0.001$).

3.2. Pupil well-being

Fig. 5 shows the mean value of the pupils' perceptions of the indoor environment. Categories in Fig. 5 (and Fig. 6) follow the order in Fig. 1, where 1 is the strongest adverse perception (most discomfort) or strongest feeling of a symptom, and 5 is no perception or symptom.

The classroom environment was rated at or above the centre scale value, indicating that the pupils on average were fairly satisfied with their classroom. The air quality and the noise level were rated lowest, which may be connected to the insufficient ventilation and the high noise level observed in many classes. Fig. 5 also indicates that with airing behaviour, pupils' perceptions of feeling cold and draught were rated lower with airing behaviour. At the same time, their perceptions of feeling warm and air quality were rated higher.

Table 4 summarises the outcome of the ordered logistic regression analysis between pupils' adverse perceptions and the airing behaviour, type of ventilation and measured physical parameters, adjusted for gender and class grade. Tables s1-s7 in the supplementary material show the detailed output from the analyses.

Table 4 shows that the airing behaviour significantly affected pupil perceptions in a direction that intuitively could be expected. Pupils felt colder or more draught with airing, which resulted in a somewhat lower temperature in the classroom, but at the same time, less warmth. The air quality was perceived as better with airing, which also decreased the CO_2 concentration and the air tem-

Table 3
Aggregated values of the CO_2 concentration, air and globe temperatures, sound pressure level and illumination.

Parameter	Uninstructed behaviour				Airing behaviour			
	Mean	Median	5th percentile	95th percentile	Mean	Median	5th percentile	95th percentile
CO_2 concentration (ppm)	1432	1100	500	3400	1103	1000	400	2400
Air temperature (°C)	22.2	22	20	25	21.6	22	19	24
Globe temperature (°C)	22.3	22	20	25	21.5	22	19	24
Sound pressure level (dB_A)	71	72	57	80	70	71	57	80
Illumination (lux)								
Condition A)	397	344	96	857	384	337	114	839
Condition B)	193	129	60	597	176	109	27	540
Condition C)	274	239	60	600	277	244	68	600
Condition D)	90	56	11	277	85	50	10	294

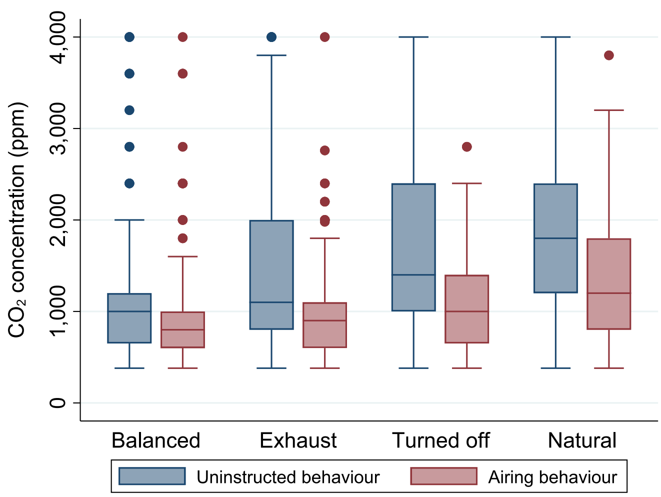

Fig. 4. CO_2 concentration distributed on the type of ventilation and behaviour.

perature. Noise and perceived darkness/brightness were also affected by the airing behaviour, possibly due to a generally more positive attitude towards the indoor environment after leaving the classroom during the break. Balanced mechanical or exhaust ventilation resulted in a better perception of several factors, but not all factors and not only those that intuitively could be expected to be connected with the ventilation type. Girls or older pupils were more critical of their indoor environment than the boys or the youngest pupils.

Fig. 6 shows that tiredness seemed to be most pronounced among the pupils, while headache scored somewhat higher and therefore was less pronounced. Fig. 6 indicates that all symptoms improved with the airing behaviour.

Table 5 summarises the outcome of the ordered logistic regression analysis between pupils' symptoms and the airing behaviour, ventilation type and measured physical parameters, adjusted for gender and class grade. Tables s8-s12 in the supplementary material show the detailed output from the analyses.

Symptoms were perceived as being significantly weaker with airing behaviour and lower temperature or noise level, whereas the measured CO_2 concentration or illumination was not associated with the symptom score. Pupils in classes with balanced mechanical ventilation generally felt weaker symptoms than those with natural/off or exhaust ventilation. Girls or older pupils felt the symptoms as being stronger than boys or younger pupils.

3.3. Concentration performance

Table 6 shows the aggregated error rate distributed on different pupil and building properties. In general, the pupils ably assessed most statements regarding the geometrical figures, and the error

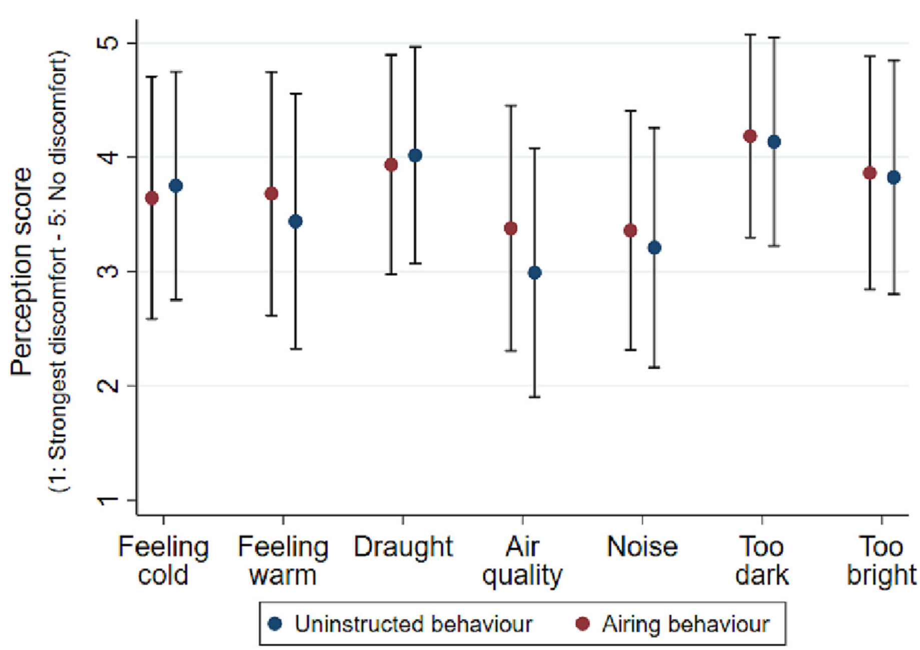

Fig. 5. Mean value of the pupils' perceptions of the classroom environment with uninstructed and airing behaviours. Error bars indicate standard deviations.

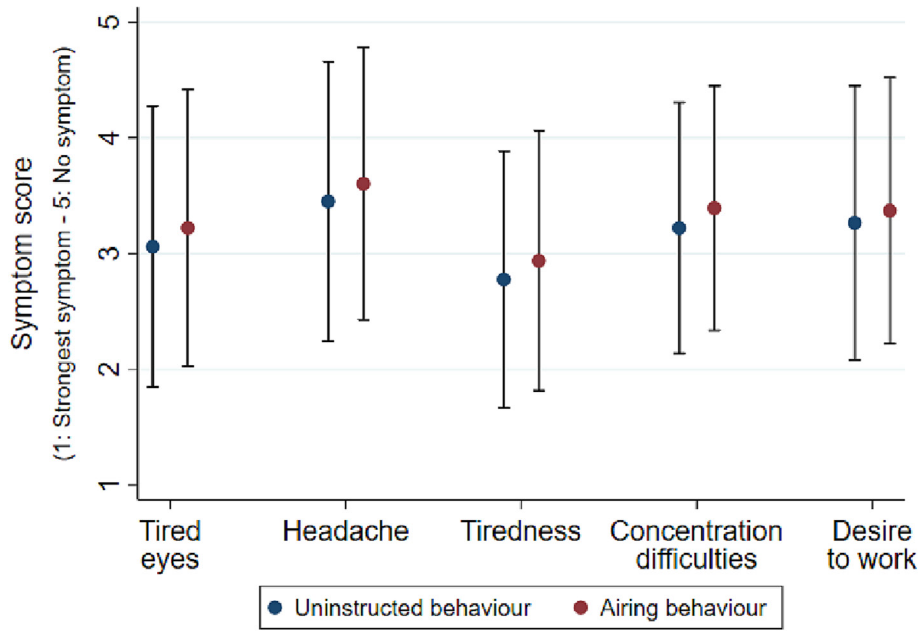

Fig. 6. Mean value of the pupils' symptoms with uninstructed and airing behaviours. Error bars indicate standard deviations.

Table 4
Summary of analyses of factors influencing pupils' perceptions (only significant associations reported).

	Airing behaviour	Ventilation type	Air temperature	CO_2-concentration	Noise	Illumination	Gender	Class grade
Too cold	*↑		**↓	**↓			**↑	**↑
Too warm	**↓	**↓	**↑	**↑	**↑	**↑	**↑	**↑
Draught	**↑	**↓	**↓	**↓			**↑	**↑
Air quality	**↓	**↓	**↓	**↓	**↓		**↑	**↑
Noise	*↓		*↑		**↑		*↑	**↑
Too dark	*↓	**↓	*↑		*↑	*↓	**↑	**↑
Too bright	*↓							**↑

Significance level indicated by * meaning $p < 0.05$ or by ** meaning $p < 0.01$.
↓indicates that pupils perceived a discomfort factor as being less annoying, e.g. that increasing air temperature or increasing CO_2 concentration resulted in a weaker feeling of being too cold. ↑indicates that pupils perceived a discomfort factor as being stronger, e.g. that airing resulted in a stronger feeling of being too cold and that girls and older pupils felt cold stronger than the boys or the younger pupils.

Table 5
Summary of analyses of factors influencing pupils' symptoms (only significant associations reported).

	Airing behaviour	Ventilation type	Air temperature	CO_2-concentration	Noise	Illumination	Gender	Class grade
Tired eyes	**↓	**↓	**↑		*↑		**↑	**↑
Headache	**↓	**↓	**↑		**↑		**↑	**↑
Tiredness	**↓	**↓	**↑		**↑		**↑	**↑
Concentration difficulties	**↓	**↓	**↑		**↑		**↑	**↑
Desire to work	**↓	**↓	*↑		**↑		*↑	**↑

Significance level indicated by * meaning $p < 0.05$, or by ** meaning $p < 0.01$↑ indicates that pupils perceived a symptom as being stronger, e.g. that increasing temperature or noise level resulted in more tired eyes and that girls and older pupils felt tired eyes more than the boys or the younger pupils. ↓indicates that pupils perceived a symptom as being weaker, e.g. that airing and balanced mechanical ventilation resulted in less tired eyes.

count was therefore low. Fig. 7 indicates that the error count distribution resembled a negative binomial distribution.

The detailed outcome of the analyses of the association between the error count and the airing behaviour, ventilation type and measured physical parameters is shown in Table s13 in the supplementary material. Across all models and as indicated by the incidence-rate ratio, airing behaviour significantly decreased the error count between 6 and 8% compared to the uninstructed behaviour. Girls consistently made 20% fewer errors than boys, and the error count of pupils in high school was around 58% lower than that of pupils in lower elementary school. The effect on the error count of the measured physical parameters was less consistent, and only the CO_2 concentration (in Model 4, where only CO_2 was included) and the air temperature indicated a weak association with the error count. Although the correlation between temperature and CO_2 was not particularly high ($r = 0.28$), their simultaneous presence in the model may have caused issues with multicollinearity. Correlations between the other explanatory variables were lower and consistently below 0.13.

As shown in Fig. 7, the errors seemingly followed an overdispersed, negative binomial distribution.

4. Discussion

In addition to stimulating interest in the natural sciences, the objective of this study was two-fold: To provide an updated account

Table 6
Mean, median, 5% and 95% percentiles of the error count distributed on class grade, gender, airing behaviour and ventilation type.

Characteristic	Mean error count	Median error count	5% percentile	95% percentile
Class grade				
- Lower elementary	2.9	1	0	10
- Middle elementary	2.7	2	0	9
- Higher elementary	2.2	1	0	9
- High school	1.5	1	0	6
- Other	1.4	1	0	5
Gender				
- Girls	2.1	1	0	8
- Boys	2.6	2	0	9
- Not indicated	2.8	2	0	10
Airing behaviour				
- Uninstructed	2.5	1	0	9
- Airing	2.3	1	0	9
Ventilation type				
- Natural	2.4	1	0	9
- System not running	2.4	1	0	9
- Exhaust only	2.4	1	0	9
- Balanced mechanical	2.3	1	0	9

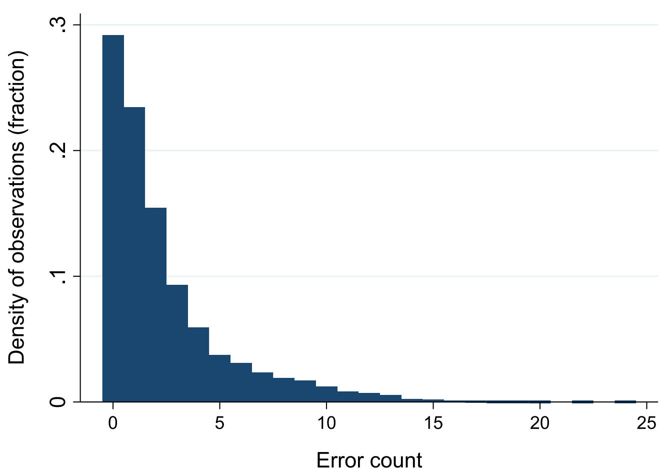

Fig. 7. Distribution of the concentration test error count. The density includes both uninstructed and airing behaviours.

of the state-of-the-art of indoor environment in Danish classrooms and to explore potential associations between the classroom conditions and pupil well-being and concentration performance based on a large-scale intervention study. Carrying out a study of this scale implied certain constraints, e.g. that the experimental activities could not be carefully controlled or closely monitored and that the use of the applied instrumentation could not be supervised. To compensate for this boundary condition of the study, efforts were made to carefully instruct teachers and pupils on how to participate in the study and to perform rigorous quality checks of the recorded data. In that regard, the study offered a premise vastly different from a tightly controlled study in a few classrooms or a laboratory setting. Also, the intervention implied that the effect on pupil responses to being outside during a break could not be separated from the effect of airing the classroom during the break. It can, therefore, not be determined if only one or the combination of these actions contributed to changing pupil responses in an overall positive direction. In the following, the measured indoor environment parameters and pupil responses are evaluated before assessing the limitations and strengths of a study of this nature.

4.1. CO_2 concentration

The current Danish building code prescribes that the CO_2 concentration in classrooms should not exceed 1000 ppm under design conditions [10]. Even so, the CO_2 concentration measured with the uninstructed behaviour was higher than 1000 ppm in 53% of the classes, which corresponded rather well with the earlier, related studies carried out in 2014 and 2009, when it was 59% and 56%, respectively [12,36]. Including only classrooms with natural ventilation through the manual opening of windows, the share of classrooms with a CO_2 concentration higher than 1000 ppm increased to 79%. Thus, despite current legislation, the air quality in many Danish classrooms continues to suffer from insufficient ventilation and poor air quality. These findings are not unusual and correspond well with other cross-sectional studies in schools both within and outside of Denmark that determined mean or median CO_2 concentrations higher than 1000 ppm [35,22,34,47,7,5], but also showed the effect on the air quality of airing the classroom [23,24,54]. With an airing behaviour that involved leaving the classroom during the break and airing out, the percentage of classrooms with a CO_2 concentration higher than 1000 ppm decreased to 36% for all ventilation types and 49 % for naturally ventilated classrooms. Thus, the effect of this behaviour pattern was clear and positive.

The frequency of classes with balanced mechanical ventilation increased from 30% in 2009 to 36% in 2014 and 38% in 2021. However, the distribution of the CO_2 concentration was nearly the same in all years, and the slightly increased prevalence of mechanical ventilation thus seemed insufficient to affect the overall distribution of the CO_2 concentration. Meanwhile, the frequency of classes relying on natural ventilation decreased from 52% in 2009 to 42% in 2014 and to 41% in 2021 (when classes with natural ventilation and ventilation systems that were turned off were merged), indicating that the distribution of ventilation type seems to have changed little since 2014, despite several information campaigns and widespread political attention in Denmark.

4.2. Temperature

Studies have shown that children prefer lower temperatures than adults and that current indoor environment standards target adult populations and do not reflect pupils in elementary school [46,15]. For indoor environment quality (IEQ) class II (medium level of expectation), which is normally used for the design and operation of buildings, CEN/TR 16798-2 (2019) recommends temperatures higher than 20 °C in the heating season. Most of the measured temperatures were higher than 20 °C and below 25 °C, indicating that classroom temperatures seemed appropriate from a thermal comfort point of view, at least for a heating season scenario corresponding to when this study was made. The pupils' responses confirmed this, as they, on average, felt neither too cold nor too warm. Yet, elevated air temperature significantly increased the intensity of their symptoms. The mean temperature decreased by 0.6 °C, and the temperature distribution generally shifted towards lower values when the classrooms were aired out. This is a natural consequence of the increased ventilation with cold outdoor air. However, with a 5%-percentile at 19 °C corresponding to the lower temperature limit of IEQ class 3, the temperatures remained mostly within a comfortable or near-comfortable temperature range. During the heating season, reheating the classroom air after intense airing will increase energy use, which underlines the dilemma between establishing good classroom air quality and maintaining high energy efficiency when heat recovery is not available. As also documented in the current study, the air exchange rate in many Danish schools is so low that an undesired energy penalty will accompany almost any mechanical solution that may increase ventilation. Yet, the non-energy benefits of better classroom air quality are sufficiently large to favour the decision to upgrade ventilation [49].

4.3. Noise

Classroom noise is a main contributor to a poor physical learning environment (e.g. [37,33]. Codes, standards and guidelines specify requirements to noise from installations and the exterior, but usually not from activities within the classroom. The measured noise levels were high but comparable to the findings of other studies in school classrooms. In two Danish schools, Kristiansen et al. [28] measured average noise levels at around 67–70 dB_A, while Larsen and Andreasen [30], in their study conducted in 50 Danish schools, found that the sound pressure level was higher than 70 dB_A in 25% of the occupied time. In 110 occupied teaching spaces in schools in London, Shield and Dockrell [44] measured an average equivalent noise level of 72 dB_A. In general, the noise measured inside the classrooms was dominated by the noise generated by the pupils, with a range of approximately 20 dB_A between the quietest and noisiest activity. A more recent study measured a somewhat lower average equivalent noise level during 274 lessons in 80 secondary school classrooms in England and Wales [43]. Most likely, the noise levels in this study were elevated as a result of the ongoing activity in the classrooms, but with mean/median values in the range of 70 to 72 dB_A do not seem to deviate much from the earlier studies in schools in Denmark and abroad, despite the use of mobile phones to record noise levels. The intensity of building-related symptoms increased consistently with increasing noise levels. In schools with a mechanical ventilation system, noise generated indoors by the installations may contribute to the pupils' and teachers' noise exposure. In schools with natural ventilation, outdoor noise may cause annoyance, affect learning performance, and prevent windows from being opened to provide ventilation [31]. However, the noise levels recorded in this study presumably resulted from the pupils' activities, which complicates a comparison of differences in noise levels caused by different types of ventilation.

4.4. Lighting

A common energy refurbishment initiative in Danish schools is to replace the existing lighting with an LED-based system. Before LED, fluorescent tubes were the most common light source. In this study, the percentage of classrooms with LED and fluorescent tubes was 27% and 65%, respectively, which supposedly will change in the coming years. Yet, the numbers indicate that upgrading the technical installations in school buildings seems slow, even though many schools may see immediate energy benefits from installing LED lighting. The Danish building code refers to DS/EN 12464–1 for the specification of criteria for artificial lighting in classrooms. The 2011 version of this standard recommends a minimum illumination of 300 lx, while the current version from 2021 recommends 500 lx. Under condition A) with lighting on and no solar shading, both mean and median illumination was higher than 300 lx but <500 lx, suggesting that the lighting system in some classrooms may not comply with the current criteria. Earlier studies in 50 classrooms in Danish schools found that the illumination was below 300 lx in around 50% of the occupied time [30,9]. At least during periods with only modest daylight, illumination thus seems too low to meet the updated recommendation of 500 lx. Illumination *per se* is important for pupil well-being and performance, but a range of other lighting quality-related parameters also need to be considered, such as glare, colour temperature, or contrast, but these were not part of this study.

4.5. Effects on pupils of their airing behaviour

Airing the classroom and leaving during the break resulted in significantly less discomfort with most of the measured perceptions of the classroom environment, except for the feeling of being cold and the feeling of draught, which were slightly more pronounced with airing. Correcting for multiple comparisons (Bonferroni correction), however, changed the perceptions of cold, draught, too bright and too dark into being non-significant. Thus, pupils consistently and significantly felt less discomfort due to feeling warm with the airing behaviour. The applied intervention particularly addressed the classroom air quality. The analyses confirmed associations between increasing temperature, increasing CO_2 concentration and poorer perceived air quality that are known mostly from laboratory experiments under well-controlled conditions [20,52]. The analyses also showed that age and gender significantly affected how the pupils perceived their classroom environment with the girls and the older pupils being the most critical.

The airing behaviour significantly affected the intensity of all symptoms that consistently were less pronounced after the classroom had been aired. Also, pupils in classes with a mechanical ventilation system felt the symptoms less severe (around 0.13 to 0.18 scale units) compared with classes with natural ventilation or a ventilation system that was not running. Elevated air temperature or noise level consistently increased the intensity of all symptoms.

The concentration test error count, which was the applied performance metric, was around 6% lower with airing than with uninstructed behaviour, indicating that not only did pupils express less concentration difficulty and a higher desire to work under this condition, but it was also reflected in the measured concentration performance. In their review of available studies, Wargocki et al. [55] found that reducing the CO_2 concentration by 1200 ppm from 2100 ppm to 900 ppm improved pupil performance as measured by the number of errors by 2%. The association between the CO_2 concentration and the error count was not significant in the current study. However, decreasing the CO_2 concentration by 1000 ppm resulted in 3% fewer errors, which was comparable with the findings of Wargocki et al. [55]. Likewise, Twardella et al. [50] found that classroom CO_2 affected the error rate but not the overall short-term concentration performance measured with a d2 test. In reading and math tests applied with boys and girls in 4th and 5th grades, Papanikolau et al. (2015) found that girls performed better than boys. The difference in performance between genders increased from around 6% in low noise level schools (55–66 dB external noise) up to 36% in high noise level schools (72–80 dB external noise), which was not too far from the 20% difference in the error count between genders in the current study.

In general, the error count was not significantly associated with the measured physical parameters. The decreased count could therefore result from the pupils' activities outside the classroom during the break. To some degree, this hypothesis is supported by Vehviläinen et al. [51], who, based on studies with adults in offices, suggested that breaks during work prevent the exhaustion of the autonomic nervous system and that relaxation periods therefore are beneficial during work. In this study, the improvement of the classroom air quality with the airing behaviour and leaving the classroom during the break to be outdoors are confounded. Both actions may have refreshed the pupils' senses and stimulated their motivation before completing the applied test.

4.6. Limitations and strengths of the study

The study's main limitation is that the approach did not allow for more rigorous control of the experiment or representative selection of schools who signed up for participation themselves. The test duration was limited to one lesson on one day under each of the two conditions, which indeed is a limiting factor when it comes to concluding. The study was carried out over six weeks and in schools across Denmark, meaning that there could be both temporal and geographical variation of the outdoor conditions, which may have affected particularly the uninstructed behaviour, i.e. if classes chose to leave the classroom in the break or to have open or closed windows during the break. Despite this variation, temperatures generally reflected moderately cold (typical) heating season conditions in Denmark, and we assume that the cross-over experimental design contributed to reducing the risk of systematic bias of the results due to the variation in the outdoor conditions. The strength of the study was the large number of participating classes and pupils. Also, balancing and randomising the order of the two experimental conditions in a cross-over design helped reduce bias from pupils not being blind to the intervention.

The applied measurement methods were far from laboratory grade, and the pupils and their teachers were inexperienced with the measurement of the indoor environment. Consequently, the raw data required comprehensive checking and processing before being analysed, implying that many records had to be discarded. In the literature, experimental approaches differ widely, as some studies rely on repeated observations in a modest number of classrooms or schools (e.g. [14,39,53,58]), while others, like the current study, involved hundreds of classrooms and thousands of pupils [1,26,44]), potentially increasing the representativeness of the findings, despite shortcomings in the scientific approach. The analyses indicated many positive outcomes of airing the classroom. However, for some of the significant outcomes, the effect sizes were so small that they had statistical more than practical value (e.g. [38]). With these outcomes, significance seemed to appear mostly due to the extraordinarily large number of responses included in the analyses. Yet, the findings of this study are generally well aligned with those from smaller-scale and larger-scale studies in schools reported in the literature.

Lower-class grades are not so well represented. The lower class grades did not have enough computers, tablets or mobile phones, and they found it difficult to respond to the questionnaires, even though these were mostly graphical. Teacher feedback indicated that these classes found completing all the study components too difficult. The results therefore represent mostly middle elementary school pupils and higher.

The applied methodology was far from the typical, well-controlled indoor environment study. If we were to carry out a comparable study in the future, a few observations could be used to improve its design: The scope of the measurements should be adapted to the grade level, as lower elementary classes and their teachers found it somewhat stressful and challenging to complete all the suggested measurements within one lesson; the online questionnaire and performance task were prepared by external programmers who lacked a deeper understanding of a study of this nature and the parameters that are needed to identify and link data. The data processing and quality assurance, therefore, required a disproportionate amount of time; our level of ambition regarding the classes' activities was very high, with rather many measurements and observations, some of which were mostly included to stimulate pupils' curiosity (e.g. measuring both radiant and air temperatures). To improve the quality of the measurements, a future protocol should consider the scope of the measurements and carefully evaluate the equipment uncertainty before implementing the measurement activities.

5. Conclusions

This study aimed to characterise the indoor environment in Danish classrooms and to explore its associations with pupil well-being and performance. Measurements were reported by a total of 709 classes in 234 schools, and 640 classes completed a building checklist. Well-being surveys were returned by 21,326 pupils and concentration tests by 20,701 pupils. Of these, a gross subsample of 13,094 responses qualified for further analysis. Statistical models analysing the association between the classroom environment and pupil well-being and concentration performance were run with between 11,106 and 12,270 of these records, depending on the model complexity.

It was found that when classes were instructed to air out the classroom and leave it during breaks to be outdoors, the air quality, as quantified by the CO_2 concentration, improved. When classes did as they usually do with no instruction of a particular airing behaviour, the CO_2 concentration exceeded 1000 ppm in 53% of the classes. The CO_2 concentration exceeded 1000 ppm in only 36% of the classes with airing. Airing also improved the pupils' perception of the classroom environment, their building-related symptoms and their performance of a concentration test in which they made 6% fewer errors than with the uninstructed behaviour.

Although measurement methods and instruments were below laboratory grade, the measured indoor environment parameters were comparable to what was found in several earlier school studies. Temperatures were mostly in a range considered to be comfortable for the heating season. Noise levels were high but agreed with findings from previous studies in Danish schools and abroad. The median illumination with artificial lighting was lower than the 500 lx recommended for classrooms but higher than the 300 lx recommended by the most recent, earlier generation of the Danish building code.

Due to the extent and nature of the study as a citizen-science project, the experimental classroom conditions could not be rigorously controlled or monitored. Instead, the validity and representativeness of the findings are supported by the amount of data and the experimental design. The study findings support that ventilation is insufficient in many Danish classrooms during the heating season. Managers of school buildings can use this knowledge to inform decisions on upgrading school buildings. Also, the study documents how appropriate airing behaviour can improve air quality with positive effects on the well-being and performance of the pupils.

Data availability

The authors do not have permission to share data.

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.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2023.112951.

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