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Association between classroom ventilation mode and learning outcome in Danish schools

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ABSTRACT

Associations between learning, ventilation mode, and other classroom characteristics were investigated with data from a Danish test scheme and two widespread cross-sectional studies examining air quality in Danish schools. An academic achievement indicator as a measure of the learning outcome was calculated from the scores of a standardized Danish test scheme adjusted for a socioeconomic reference index. Pupils in schools with balanced mechanical ventilation had significantly higher achievement indicators than pupils in schools with natural ventilation, where airing took place mostly by manual window opening. Also, the carbon dioxide concentration was lower in classrooms with balanced mechanical ventilation. There was no consistent association between the achievement indicators and the person specific room volume, construction/renovation year, or the occupancy. Measurements of carbon dioxide concentrations and temperatures in 820 classrooms in 389 schools were available. In 56% and 66% of the classrooms included in the two studies, the measured CO_2 concentration was higher than 1000 ppm. The findings of this study add to the growing evidence that insufficient classroom ventilation have impacts on learning outcomes.

1. Introduction

Poor classroom environmental conditions are common and have been associated with reduced pupil well-being and performance of schoolwork e.g. Refs. [1–7]. Air-conditioning, classroom illumination, temperature control, building layout and age are among the additional factors that have been identified as potentially influencing the performance of pupils [8]. Also, several studies have shown elevated carbon dioxide concentrations in classrooms resulting from a lack of systems dedicated to achieving proper ventilation e.g. Ref. [9]. This is reflected in the high carbon dioxide concentrations typically measured in classrooms indicating insufficient ventilation. Reduced pupil well-being and performance caused by substandard classroom conditions may lead to a reduced learning outcome, which ultimately may have economic consequences both at individual and societal level [10,11].

Previous studies examining the effects on learning of the indoor environment in classrooms used mainly psychological and neurobehavioural tests to examine different skills needed for proper learning, such as the ability to concentrate and memorize [12–14], as well as shorter tests examining the ability to read, comprehend and calculate [4,5]. The latter study showed that poor classroom ventilation can significantly reduce the ability to perform these tests. Although the long-term learning outcomes are also expected to be affected by the absence of such skills, the connection between the progress in learning and psychological and neurobehavioural tests is not well documented.

General learning outcomes can be monitored with standardized tests, which are often developed by national or regional education departments. These tests monitor and benchmark both individual pupils and schools as well as evaluate the effectiveness of teaching methods and curricula. Haverinen-Shaughnessy et al. [6] used such tests to show that poor ventilation in classrooms reduced the number of pupils just passing language and math tests.

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Standardized tests are applied regularly during the school year, but it may be challenging to acquire matching and representative information on the classroom conditions. Furthermore, it cannot be ruled out that the test outcome is influenced by factors not related with the indoor environment in classrooms, including socioeconomic status, teaching methods, or teacher quality.

Increased illness absence may be another consequence of poor classroom ventilation, which indirectly can lead to a decreased learning outcome. Ervasti et al. [15] found increased short-term sick leave among teachers in schools with poorly perceived indoor air quality. Shendell et al. [3] found student absence to decrease by 10–20% when the CO_2 concentration decreased by 1000 ppm in 434 American classrooms. A somewhat smaller effect size was found by Gaihre et al. [16] in their study in 60 naturally ventilated primary school classrooms in Scotland, where an increase of 100 ppm CO_2 was associated with a reduced annual attendance of 0.2%. Simons et al. [17] found high student absenteeism to be associated with poor ventilation rating (e.g. malfunctioning, dirty filters, blocked vents, etc.) in 2751 New York schools, and Simoni et al. [18] found that school children exposed to CO_2 levels below 1000 ppm had a significantly lower risk of dry cough and rhinitis. A recent and very comprehensive study in 162 Californian classrooms observed that pupil illness absence decreased by as much as 1.6% for each additional 1 l/(s person) increase in the ventilation rate [10]. Although these findings still need confirmation, they suggest that increasing classroom ventilation may substantially decrease illness absence and thereby indirectly affect the learning experience. However, although intuitively likely there is still no clear evidence of an association between the short-term absence of pupils and academic performance [2]. Furthermore, absence rates can be influenced by many factors not necessarily related with school environments, such as the health status of the pupils, the sensitivity of their immune system, conditions at home, etc.

The aim of this paper was to study associations between ventilation mode and other classroom-related parameters and learning as measured with the Danish national test scheme. Other classroom related parameters included school year, room volume, construction/renovation year, occupancy, window opening frequency, and window orientation. Also, the results of two cross-sectional studies examining the air quality in 820 classrooms from 389 Danish public schools will be presented.

The paper is organized as follows. Section 2 is devoted to the Materials and methods, which describes how data used in the analyses were obtained from two field studies in Danish schools and from a standardized national test scheme. The section also describes how data were processed and combined as well as the analyses used to study the associations between school characteristics and learning outcome. Section 3 presents the results of the measurements and observations in the field studies and, after combining field study data with records of national test scores, the associations between classroom characteristics and test scores. Section 4 discusses the findings and in particular the limitations of the study. Section 5 presents the conclusions.

2. Materials and methods

2.1. Approach

A retrospective analysis was performed in which results from the Danish national test scheme collected in the school year 2009–2010 were associated with parameters describing the ventilation conditions and other classroom characteristics in a subset of schools included in the two cross-sectional studies. This information was obtained through surveys in classrooms carried out in late 2009.

2.2. Assessment of classroom environments

The first cross-sectional study (*study I*) consisted of measurements from 311 elementary and high schools (Fig. 1). Indoor environmental conditions were measured in one to sixteen classrooms per school (732 classrooms in total from pre-school to elementary school through third year high school). *Study I* ran from September to October 2009.

Study I was organized by the Danish Science Communication (now Danish Science Factory, http://naturvidenskabsfestival.danishsciencefactory.dk) with scientific support from the authors of this paper. The Danish Science Factory is a non-profit organisation that works to engage pupils in the natural sciences through a yearly natural science festival. The 2009 festival aimed to engage pupils in examining the indoor environment in their classrooms. One-thousand classes signed up voluntarily for participation in the festival as a part of their science classes, but only 732 provided meaningful measurements. Locations of the schools participating in the festival were almost evenly distributed in Denmark.

Each class was provided with equipment to measure the CO_2 concentration, air temperature and mould (mould measurements are not reported in this paper). Spot measurements were performed by the pupils at the end of a lesson during which the pupils were asked to keep the windows in the classroom closed to mimic a worst-case though realistic heating season scenario. All other classroom behaviour and settings for heating and ventilation systems were unaffected by the measurements.

Each class made only one measurement of the CO_2 concentration during one lesson. This lesson could be selected without restrictions during the three-week experimental period (from 14th September until the 2nd October). During this period, the outdoor temperature varied between 0 °C during the coldest nights and up to 23 °C during the warmest days.

The CO_2 concentration was measured with a Kitagawa 126SF measurement tube (range: 200–4000 ppm, relative standard deviation: 10%). Temperature was measured with a thermometer provided by the school. The measurement data was then transferred to a central server via a dedicated homepage. Pupils and their teacher also entered information regarding the classroom characteristics, including ventilation mode, room volume, and occupancy.

The second cross-sectional study (*study II*) was performed from October to December 2009. It comprised continuous measurements in one randomly selected classroom at each of 88 randomly selected elementary schools. The CO_2 concentration was monitored at 5 min intervals during an average of 17 consecutive days (range 4–35 days). Measurements were performed with a Vaisala model GMW22 (CO_2 range: 0–5000 ppm ± 100 ppm + 2% of reading) connected to a HOBO data logger model U12-012 (signal range: ± 2 mV ± 2.5% of reading) that also monitored temperature and relative humidity in the classroom. The loggers were deployed in the schools by janitors or teachers, who were instructed on how to place them. During the measurements, teachers and pupils assessed perceptions of temperature, indoor air quality, odour, lighting, noise, and cleanliness of the classroom using a paper-based questionnaire. They also provided information on the classroom characteristics, including ventilation mode, room volume, and occupancy. CO_2 and temperature data were extracted for school days only, which were defined as weekdays from 8 am to 2 pm based on an evaluation of the typical school day of 20 of the participating classes, which spanned from around 8 am to between 1.30 p.m. and 2.30 p.m. For each school, grand means, maximum, and 20 min running mean for the occupancy period were calculated. During the study period, the outdoor temperature ranged from 0 °C to 15 °C. There was an overlap of ten schools between *study I and study II* resulting in a total of 389 unique schools.

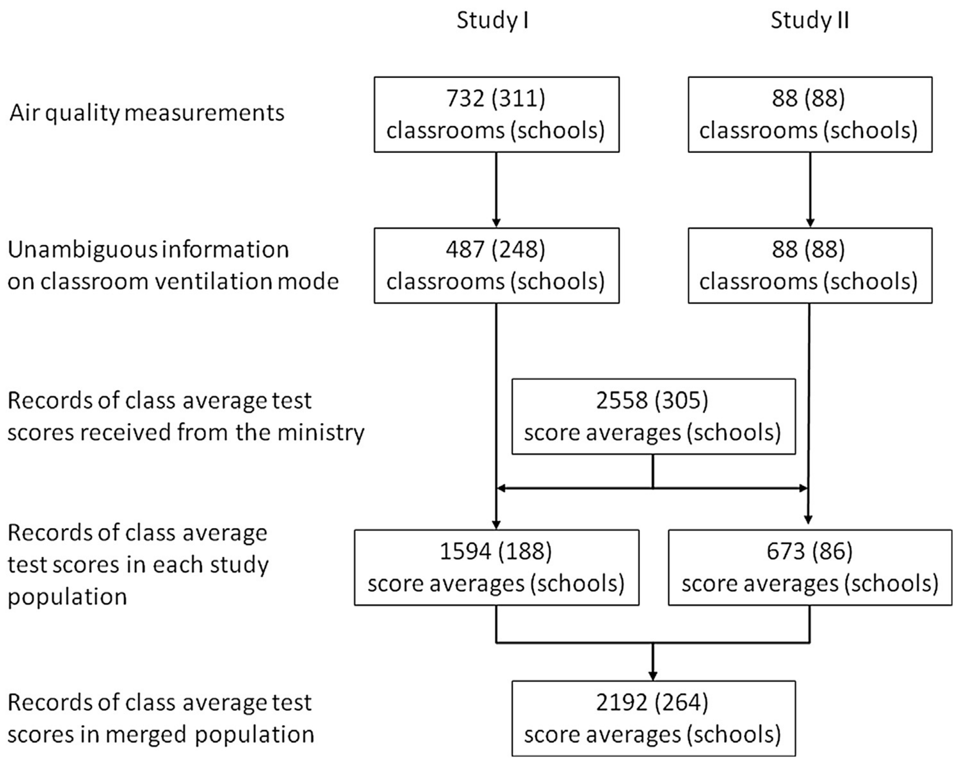

Fig. 1. Flow chart showing the number of classrooms, schools and test score averages used in the different stages of the analysis.

2.3. Quantification of academic achievement

To quantify academic achievement, scores from a standardized Danish national test scheme were used. These results were obtained from the Danish Ministry of Education and consisted of test scores for the school year of 2009–2010 to best match the time period of *study I* and *II*. Test scores were obtained at class level for the majority of schools participating in the two studies. Fig. 1 shows a flowchart that illustrates data reduction through the different stages of the analysis.

The Danish national test scheme has been used in Denmark since 2007 and it was fully implemented in 2010. It is applied to measure the academic performance of primary school pupils and serves as an official benchmark for public primary education quality. The national test scores are used to evaluate pupil performance, to adjust individual pupil and class goals and to adjust the teaching according to the pupils' individual needs. The test scheme includes 10 online progressive mandatory tests that are presented to the pupils through the second to fourth grades and the sixth to eighth grades. They examine language fluency (reading and comprehension in Danish) in the 2nd, 4th, 6th and 8th grades, competency in math in the 3rd and the 6th grade, knowledge of English in the 7th grade, and knowledge of physics/chemistry, geography and biology examined in the 8th grade. Three focus areas within each subject are tested. For example, algebra, geometry, and applied math are three focus areas in math. The data obtained for the present analyses included tests scores for each of the test subjects.

The teachers oversee pupils during the test sessions after which the raw test results are submitted to the Ministry. Here the results are processed and analyzed and the percentage of correct answers are calculated within each focus area and for the test subject as a whole (average of the focus area scores within a given test subject). In this form they are reported back to the schools at pupil and class levels. We used these standardized test scores at class level in our analyses.

The test scores are adjusted for socioeconomic factors using a socioeconomic reference index. The socioeconomic reference index is a statistically determined baseline that is used to compare the score of the pupils at a given school with the average score of pupils with the same socioeconomic status. The socioeconomic reference index is calculated by the Ministry of Education based on gender, age, ethnicity and country of origin, parents' highest level of education, parents' income, employment, family status (couple, single), number of children in the family and rank of the child, and interaction between gender and ethnicity. At school level, the index also takes into account the percentage of immigrants and their descendants among the pupils.

2.4. Data processing

The two measurement campaigns in *study I* and *study II* provided input to two datasets with temperature and the CO_2 concentration measured in one or a few classrooms at a school. In both studies the classroom ventilation mode was reported along with other school building characteristics. In analyses where the ventilation mode and other school characteristics were used as independent variables the two individual datasets were merged, as similar methods were used to collect the information on building characteristics, but not to measure temperature and CO_2. Fig. S1 (Supplementary material) illustrates the most common ventilation setups in classrooms with natural ventilation by window opening, balanced mechanical ventilation, and mechanical exhaust ventilation.

Using the data from the national tests we calculated an achievement indicator, defined as the difference between a student's unadjusted test score and the average score of all pupils with the same socioeconomic reference index. The adjustment of test scores with the socioeconomic reference index is intended to make scores more comparable so that residual differences after adjustment represent school-related effects. A positive achievement indicator corresponded to a performance above average and negative below average. The outcome variable in the analyses was the achievement indicator averaged at class level after merging scores across all tests in different subjects as well as separately for each subject.

Measurements were made only in a few classrooms (*study I*) or in one classroom (*study II*) at each school. It was therefore not possible to link directly the temperature and the CO_2 concentration measured in a given classroom with the achievement indicator of a particular class that occupied mostly that room. Also, CO_2 concentrations and temperatures vary between classrooms; in particular at schools with natural ventilation by manual window opening. It was therefore decided to use the school's ventilation mode as a proxy of the indoor environment exposure along with other building related parameters. Also, this allowed us to increase the statistical power of the analyses by including national test scores for all classes at a school for which data was available.

Schools that provided data from more than one classroom and where reports on the ventilation modes in the classrooms were ambiguous were excluded from the analyses. Records obtained with fewer than four pupils present in the classroom or where the person specific room volume was lower than 3.5 m^3/person were omitted from analyses where classroom occupancy and room volume were included. Records from schools or classes in which the ventilation mode was unknown, automated natural ventilation or mechanical supply only were also omitted from the analyses.

2.5. Data analysis

The measured CO_2 concentrations did not follow a Gaussian distribution and therefore the non-parametric Pearson chi-squared test of the equality of the medians was used to test associations between the CO_2 concentration or the temperature and building characteristics (ventilation mode, school year, person specific room volume, construction/renovation year, occupancy, window opening frequency, and window orientation) [19].

Univariate logistic regression analysis was used to study associations between the average CO_2 concentration measured in *study II* and teacher and pupil perceptions of stuffy and odorous air assessed on a binary scale (stuffy air/not stuffy air, odour/no odour).

Achievement indicators were analysed in Gaussian generalized linear models (GLM) with an identity link function, clustered on schools and weighted by the number of pupils at class level representing the average achievement indicator. The achievement indicator was used as dependent variable and the ventilation mode, the person specific room volume, construction/renovation year, occupancy, and in *study II* the window opening frequency and window orientation were used as independent variables (analysis of the effect of ventilation mode adjusted for the effect of other building characteristics). After running the GLM, pair-wise tests of the parameters of the model were carried out with a Wald test [20]. It was ascertained that residuals followed a Gaussian distribution. All analyses were carried out with Stata IC version 12.0 (Statacorp, TX, USA).

3. Results

3.1. Classroom air quality

Fig. 1 gives an overview of the number of schools and records of class average test scores that were used in the different analyses. It is not uncommon that schools comprise different generations of buildings and therefore some schools reported different ventilation modes in the classrooms (e.g. reports from the same school indicated both natural and mechanical ventilation). However, in the analyses of achievement indicators we restricted data so that schools with ambiguous reports on the ventilation mode were omitted from analyses that included this variable. Thus, we excluded schools with reports on multiple ventilation modes and schools that represented very rare ventilation modes. Altogether there were 264 schools for which information on the ventilation mode and on achievement indicators were available and could be analyzed.

Fig. 2 shows the cumulative distribution of the CO_2 concentration measured in the two studies. In *study I* only instantaneous (spot) measurements of CO_2 were available and they were used as an indicator of the indoor air quality; the measured CO_2 concentration ranged from 400 ppm to 4000 ppm, which was the upper limit of the detection tube used for the measurement (median 1200 ppm). In *study II*, the running mean concentration ranged from 578 ppm to 2183 ppm (median 1261 ppm) and the maximum values of the running mean ranged from 900 ppm to 4597 ppm (median 2479 ppm). In 66% of the classrooms in *study II* the average CO_2 concentration was above 1000 ppm and 66% of the classrooms experienced 20 min periods with CO_2 concentrations above 2000 ppm. In 56% of the classrooms in *study I*, the measured CO_2 concentration was above 1000 ppm. The questionnaire distributed among pupils and teachers in *study II* indicated that the perception of stuffy and odorous indoor air was more prevalent with increasing CO_2 concentration ($p < 0.01$; univariate logistic regression).

Fig. 3 shows boxplots of the temperatures by ventilation mode as measured in the two studies. Generally, the temperatures varied more and in a wider range in study I than in study *II*. Although not significant in any of the two studies ($p > 0.05$; median test), Fig. 3 indicates that in *study I*, the temperature was slightly lower in the classrooms with balanced mechanical ventilation than in the naturally ventilated classrooms, where airing took place mostly by manual window opening. This trend was opposite in *study II*. In *study I*, temperatures (spot measurements) ranged from 14 °C to 30 °C (mean 22.3 °C, s.d. 1.8 °C). The maximum temperature measured in each classroom in *study II* ranged from 20.3 °C to 27.0 °C (mean 23.4 °C, s.d. 1.2 °C), while the average temperatures ranged from 18.5 °C to 23.7 °C (mean 21.4 °C, s.d. 1.0 °C). With a few exceptions, temperatures measured in both studies agreed with recommendations in thermal comfort standards for winter conditions indicating that at least during the early heating season, temperature conditions in the classrooms were not compromised e.g. Ref. [21].

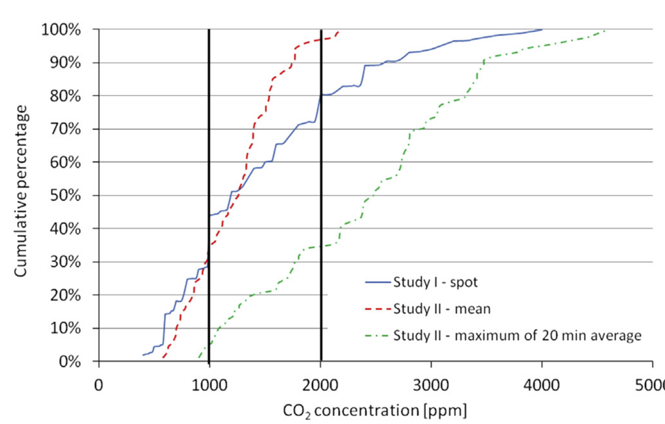

Fig. 2. Cumulative distribution of the CO_2 spot measurement in *study I* ($n = 732$) and the average and maximum (20 min running average) CO_2 concentration in *study II* ($n = 88$).

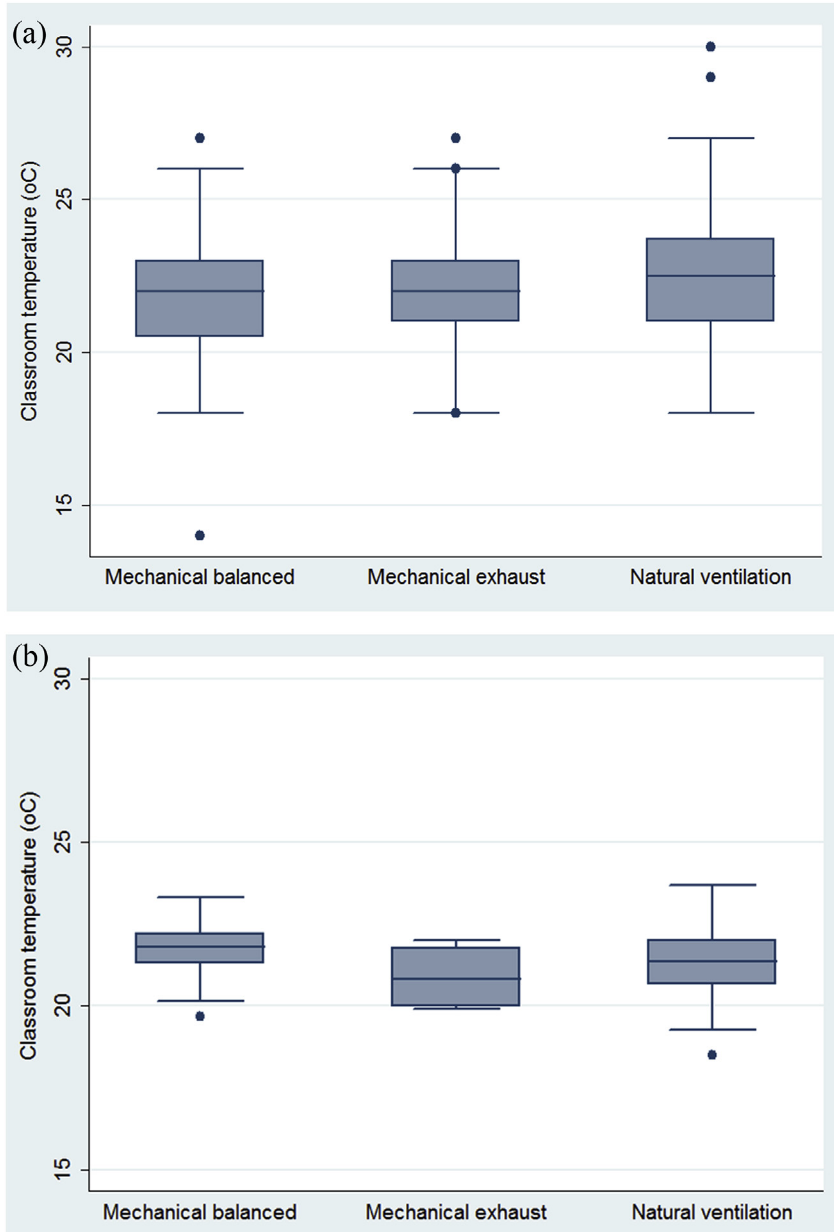

Fig. 3. Boxplot of the temperatures measured with different ventilation modes in *study I* (3a) and in *study II* (3b).

Table 1 summarises the median CO_2 concentration stratified by different building characteristics, such as ventilation system, school year, nominal person specific classroom volume, construction/renovation year of the school, occupancy, window opening frequency, and window orientation. The table shows that the ventilation mode was significantly associated with the measured CO_2 concentration ($p < 0.01$, median test), which was lowest in classrooms with balanced mechanical ventilation systems compared with the classrooms with only mechanical exhaust or with natural ventilation, in which the highest CO_2 concentrations were measured.

In *study I*, a reduction of the person specific room volume and an increase of the occupancy significantly and systematically increased the CO_2 concentration ($p < 0.01$, median test). The highest CO_2 concentrations were measured in the oldest school buildings or buildings that were renovated more than 40 years ago ($p < 0.01$, median test). Also, the oldest buildings were more often naturally ventilated. This trend may reflect the development of the Building Code in Denmark, which first in 1995 included provisions for mechanical ventilation systems in schools. Generally, buildings constructed and renovated before this date can be inferred to have natural ventilation (airing by manually operable windows). The possible difference in air tightness between the newer and older school buildings most likely were inferior to the CO_2 generation rate and presumably less important for the measured CO_2 concentration due to the high CO_2 generation rate in densely occupied classrooms. Although not significant, an unexpected inverse relationship between the window opening frequency as reported by the classes and the CO_2 concentration was observed in *study II*.

The measured temperatures did not vary systematically with the ventilation mode, class grade, person specific room volume, construction/renovation year, occupancy, window opening frequency, or window orientation (data not shown).

Table 1
Median of the CO_2 concentrations measured in *study I* (spot) and summary of the concentrations from *study II* (median of maximum 20 min running average and inter-quartile range of the maximum values) stratified by different school characteristics.

	CO_2 concentration (ppm)				
	Study I		*Study II*		
Parameter	Median	n	Median of maximum 20 min running average	Inter-quartile range, maximum 20 min running average	n
Ventilation mode		732			85
1 Natural ventilation	1600	379	2875	2384-3359	44
2 Mechanical exhaust	1200**1	130	2372**1	1798-2492	10
3 Mechanical balanced	1000**1,2	223	1344**1,*2	1066-2170	31
School year		538			–
1 Kindergarten-3rd year	1200	123	–	–	–
2 4th-6th year	1300	208	–	–	–
3 7th-9th year	1300	207	–	–	–
Person specific room volume		665			79
1 < 10 m^3/person	1450	364	2451	1723-3282	52
2 10–19.99 m^3/person	1000**1	256	2476	1606-3069	27
3 ≥ 20 m^3/person	850**1,*2	45	–	–	0
Construction/renovation year		709			86
1 < 1950	1700	116	2174	1625-3055	7
2 1950-1974	1500	277	2813	2559-3411	19
3 1975-1999	1000**1,2	220	2385*2	1719-3069	23
4 ≥ 2000	1000**1,2	96	1866**2	1142-2885	37
Occupancy		717			87
1 < 15	1000	108	2283	1977-2683	10
2 15-19	1300*1	223	2737	2072-3141	22
3 20-24	1300**1	276	2627	1730-3214	42
4 ≥ 25	1400**1	110	1693**2,*3	1079-2373	13
Window opening frequency	–	–			83
1 Several times per day	–	–	2796	1797-3412	33
2 At least once per day	–	–	2385	1523-2776	41
3 Less than once per day	–	–	1344	995-2680	9
Window orientation		–			65
1 North	–	–	1729	1165-3165	8
2 South	–	–	2765	2227-3285	25
3 East	–	–	2357	1706-2767	13
4 West	–	–	2385	1134-3365	19

*$p < 0.05$, **$p < 0.01$, numbers refer to the factor levels that were compared with a non-parametric Pearson chi-squared test of the equality of the medians and for which there was a significant difference.
In *study I* the median was calculated based on the single measurement made by each class. In *study II* the median was calculated based on the maximum of the 20 min running average for the occupancy period for each class.
Schools with mechanical supply only or automatically controlled natural ventilation were very few and were not included in the analysis. Therefore the number of schools indicated in the table is slightly lower than in Fig. 1.
n shows the number of classrooms.

3.2. Achievement indicators

Table 2 shows the achievement indicators stratified by different building characteristics as shown in the table. Due to the modest robustness and representativeness of the measured CO_2 concentration as an indicator of the indoor air quality in schools with many classrooms, we used a schools ventilation mode as the main independent variable in analyses of the association between building characteristics and the achievement indicator. Also, this enabled us to merge the datasets from the two studies and increase the power of the analyses. Naturally ventilated schools had significantly lower achievement indicator compared with schools with balanced mechanical ventilation (relative difference of 1.45% points, $p < 0.05$, GLM). Schools with mechanical exhaust had the highest average achievement indicator being almost the same as in schools with balanced ventilation. This suggests that pupils in schools with some means of mechanical ventilation on average scored higher in the national tests than pupils in schools with natural ventilation. Table 2 also shows that there was not a similarly consistent association between the achievement indicator and the person specific room volume, construction/renovation year, or occupancy.

Table 3 shows associations between ventilation type and achievement indicators individually for each subject area. With the merged datasets, the naturally ventilated schools had the lowest achievement indicator for all subject areas, although only significantly lower than schools with balanced mechanical ventilation for the subject areas "Danish" (1.29% point, $p < 0.03$, GLM) and "math" (1.96% points, $p < 0.02$, GLM). With the *study II* dataset, schools with natural ventilation had the lowest achievement indicator in five out of six subject areas, although this was only significant for "English" (3.27% points, $p < 0.03$ as compared with balanced mechanical ventilation, GLM) and for "physics/chemistry" (4.68% points, $p < 0.04$, as compared with mechanical exhaust, GLM). Using only the *study I* dataset, schools with natural ventilation had the lowest achievement indicator in four out of five subject areas. The difference was significant only for "math" (2.63% points, $p < 0.01$, GLM) and "English" (1.55% points, $p < 0.05$, GLM).

4. Discussion

The results of this study showed that pupils in schools with natural ventilation in which airing took place by manual opening of windows

Table 2
Achievement indicators stratified by different building characteristics.

Parameter	Achievement indicator					
	Merged datasets	Schools	*Study I*	Schools	*Study II*	Schools
Ventilation mode		261		188		83
1 Mechanical balanced	1.10	82	0.99	55	1.22	30
2 Mechanical exhaust	1.14	34	1.16	24	1.09	10
3 Natural ventilation	−0.35*1	145	−0.29*1	109	−0.38**1	43
Person specific room volume		257		188		78
1 < 10 m^3/person	0.19	131	0.15	88	0.32	51
2 10–19.99 m^3/person	0.57	101	0.59	75	0.66	27
3 ≥ 20 m^3/person	0.25	25	0.11	25	–	–
Construction/renovation year		262		188		84
1 < 1950	0.60	27	0.58	22	0.75	7
2 1950-1974	−0.10	100	−0.19	83	0.51	19
3 1975-1999	0.37	73	0.44	53	0.25	23
4 ≥ 2000	1.04	62	1.43	30	0.45	35
Occupancy		262		187		85
1 < 15	−0.52	31	−0.28	22	−1.81	9
2 15-19	0.65	89	0.70	70	0.58	22
3 20-24	−0.24	112	−0.25	76	−0.09	41
4 ≥ 24	2.17	30	2.26**3	19	1.67	13
Window opening frequency		–		–		81
1 Several times a day	–	–	–	–	0.68	33
2 At least once a day	–	–	–	–	−0.02	39
3 Less than once a day	–	–	–	–	0.66	9
Window orientation		–		–		64
1 North	–	–	–	–	0.38	8
2 South	–	–	–	–	1.24	25
3 East	–	–	–	–	−1.30	13
4 West	–	–	–	–	0.95	18

*$p < 0.05$, **$p < 0.01$. Numbers refer to comparison of factor levels for which there was a significant difference.
Schools with mechanical supply only or automatically controlled natural ventilation were very few and were not included in the analysis. Therefore the number of schools indicated in the table is slightly lower than in Fig. 1.
Analysis of the effect of the ventilation mode was adjusted for the available building related characteristics person specific room volume, construction/renovation year, occupancy, and in the analysis of data from *study II* for window opening frequency and window orientation.

generally scored lower in the national tests than did pupils in schools with balanced mechanical ventilation. Also, it was clear that the indoor air quality in the naturally ventilated schools was poorer as indicated by elevated CO_2 concentrations measured in the classrooms in these schools. Although this was the very first and preliminary analysis carried out retrospectively using non-aligned datasets, the findings add to the growing evidence that poor air quality in schools may have detrimental effects on the long-term learning outcomes.

A limitation of the present study is that schools in *study I* signed up for participation themselves and that observations and measurements were made by laypersons. A more desirable design would have been a progressive study including randomly selected schools with monitoring of the CO_2 concentration during the entire school year, e.g. as done by Mendell et al. [10]. However, this was not an option in the current study and one of the reasons for using the rather crude classification of the ventilation mode as independent variable in the analyses. Also, the national test scheme was not yet fully implemented and it was therefore not possible to retrieve test scores from all schools where measurements were made in *study I* and *study II*.

Another limitation is that the CO_2 concentrations may not represent well the actual air quality conditions in the classrooms across seasons. This applies especially to *study I* in which spot measurements of the CO_2 concentration were performed by the pupils in a heating season scenario because windows were closed during the entire lesson prior to the measurements made at the end of the lesson. It can be expected that the ventilation rate and the CO_2 concentration in classrooms with mechanical systems are more or less constant during the entire school year, assuming that the class occupancy is unchanged and that the system uses similar settings during different seasons. However, in schools with naturally ventilated classrooms in climate zones characteristic of Denmark, indoor CO_2 concentrations are much higher in winter (heating season) than in summer [9]. In such schools, the CO_2 concentration highly depends on pupil and teacher behavior, which further contributes to the variation of the CO_2 concentration between classrooms and schools, much more than in schools with balanced mechanical ventilation [9].

The variation of the CO_2 concentration between classrooms was quantified by Wohlgemuth and Christensen [22] who studied a large number of classrooms in two Danish schools, one with natural ventilation by manually operable windows (22 classrooms) and one with balanced mechanical ventilation (11 classrooms). They found that in the school with natural ventilation, the range of the maximum CO_2 concentration was more than three times wider than in the mechanically ventilated school (2600 ppm vs. 750 ppm). Likewise, the range of the average CO_2 concentration was more than two times wider in the naturally ventilated than in the mechanically ventilated school (700 ppm vs. 300 ppm). However, the day-to-day variation of the CO_2 concentration within a classroom seemed rather modest [22,23] Thus, there may be considerable seasonal and spatial variation of the CO_2 concentration. The ventilation mode of a school was therefore considered to be more robust and better represent the indoor air quality and thermal exposure within a school, even though this is a crude classification that does not account for the maintenance and cleanliness of the system, its actual performance, frequency of filter change in

Table 3
Achievement indicators analysed for all or each individual subject area and for different ventilation modes.

Ventilation mode	Achievement indicator					
	Merged datasets	Schools	*Study I*	Schools	*Study II*	Schools
All						
		261		188		83
1 Mechanical balanced	1.10	82	0.99	55	1.22	30
2 Mechanical exhaust	1.14	84	1.16	24	1.09	10
3 Natural ventilation	-0.35^{*1}	145	-0.29^{*1}	109	-0.38^{**1}	43
Danish						
		259		187		82
1 Mechanical balanced	1.05	81	0.82	55	1.54	29
2 Mechanical exhaust	1.26	34	1.25	24	1.29	10
3 Natural ventilation	-0.24^{*1}	144	−0.22	108	0.03	43
Math						
		258		185		83
1 Mechanical balanced	1.19	81	1.54	54	0.16	30
2 Mechanical exhaust	1.18	33	2.39	23	−1.28	10
3 Natural ventilation	-0.77^{*1}	144	-1.09^{*1}	108	0.47	43
English						
		199		147		57
1 Mechanical balanced	1.49	65	1.36	46	1.96	22
2 Mechanical exhaust	1.44	29	1.08	20	2.24	9
3 Natural ventilation	-0.40^{*1}	105	-0.19^{*1}	81	-1.31^{*1}	26
Physics/chemistry						
		186		142		49
1 Mechanical balanced	0.45	58	0.03	42	1.33	19
2 Mechanical exhaust	1.07	26	0.44	20	2.59	6
3 Natural ventilation	−0.33	102	0.22	80	-2.09^{*2}	24
Biology						
		180		138		47
1 Mechanical balanced	1.84	57	1.60	41	2.11	19
2 Mechanical exhaust	0.53	25	0.05	19	1.83	6
3 Natural ventilation	0.16	98	0.30	78	−0.10	22
Geography						
		179		135		49
1 Mechanical balanced	0.68	57	0.58	41	0.32	19
2 Mechanical exhaust	0.80	24	0.03	18	2.99	6
3 Natural ventilation	−0.41	98	−0.02	76	−2.08	24

$^{*}p < 0.05$, $^{**}p < 0.01$. Numbers refer to comparison of factor levels for which there was a significant difference.
Schools with mechanical supply only or automatically controlled natural ventilation were very few and were not included in the analysis. Therefore the number of schools indicated in the table is slightly lower than in Fig. 1.
Analysis of the effect of the ventilation mode was adjusted for the available building related characteristics person specific room volume, construction/renovation year, occupancy, and in the analysis of data from *study II* for window opening frequency and window orientation.

mechanically ventilated schools, etc.

In *study I*, teachers themselves signed up for participation in the experiment increasing the risk of selection bias toward the engaged teachers and motivated students. However, we do not expect any selection bias that relate to the ventilation mode of the schools, which was the main independent parameter in the analyses. We therefore assume that our findings will not be affected by potential selection bias toward student aptitude and teacher engagement. If such bias existed in the applied data, our findings would target mostly classes with able students. Also, a limitation of *study I* was the lack of rigorous quality control of the measurements and the observations made by the classes, which introduces the possibility of either overestimation or underestimation of the CO_2 concentration and misclassification of the ventilation mode (the latter also applies to *study II*). This is likely to have been a random event and so is not expected to have introduced any systematic bias in the analyses. Also, the distribution of school ventilation modes in the two studies was comparable as indicated in Table 1.

Despite these limitations, the results are in line with the findings of Haverinen-Shaughnessy et al. [6] and show the negative effects on learning of poor air quality in the classroom. Compared with the study by Haverinen-Shaughnessy et al. the present study used a more comprehensive scheme to monitor the learning outcome. The compulsory national test scheme developed by the Ministry of Education in Denmark examines learning across different subject areas and across different class-grades, while Haverinen-Shaughnessy et al.'s analysis was limited to pupils passing language and math tests in the fifth-grade. The effects observed in their study seemed higher than in the present analyses: Increasing the ventilation rate by 1 L/s per person increased the number of pupils passing the test by about 3%. In the present study, the ventilation rates in the classrooms were not estimated, but under the assumption that the classrooms were occupied by almost the same number of pupils, the median CO_2 concentrations in Table 1 suggest that the ventilation rates in classrooms with a balanced mechanical ventilation system were approximately twice as high as in classrooms with natural ventilation. The relative difference in the achievement indicators between mechanically and naturally ventilated classrooms was only about 2%. Other studies support an equivalent association between poor ventilation in classrooms and reduced speed at which tasks that are typical of schoolwork are performed, although the effect in some cases was stronger than in this study [7,24]. Poor classroom air quality can also increase absenteeism [3,10], which then indirectly and negatively may affect the learning outcome.

In this study national test scores were available only as class averages, which restricted the analytical approach to rather simple statistical models. Although the variation in socio-economic status between different parts of Denmark generally is modest, the national test scores were adjusted for this important covariate as it may be one of the most important factors for the learning outcome e.g. Ref. [25]. In previous analyses of the final examination grade of Danish primary schools, the socioeconomic reference index explained 9–22% of the total inter-pupil variance and 17–62% of the inter-school variance, depending on the test subject [26]. Knowledge of the background values used to calculate the socio-economic reference index was not available in the present analyses, but the index was calculated by the Division of Statistical Analysis of the Ministry of Education that is administering the national tests [26].

The poorer achievement recorded among pupils in naturally ventilated classrooms was seen for all different subjects from Danish to geography, but the difference was significant only for some subjects. One explanation for this result could be that the tests for these subject areas were presented to pupils in several grades. Consequently, the number of records in the analyses was higher than for other subjects increasing the chance of observing non-random differences. Another reason could be that the effects of poor indoor air quality on learning are best manifested when basic skills and abilities are examined, such as for example reading and math. In case of geography or foreign language fluency, which may be broader in nature and require more comprehensive competencies, the effects of poor indoor air quality may not be that evident. It is important to note that basic knowledge of math and fluency in native language are considered to be essential prerequisites for proper progress in learning. They are also recognized by a recent report published by the OECD, which states that poor skills in mathematics severely limit people's access to better paying and more-rewarding jobs [27].

We have not found any earlier studies that associated academic performance and classroom ventilation mode and also no evidence that in office settings, the ventilation mode *per se* affects cognitive performance. Even if ventilation mode is a crude proxy of the indoor air quality, we generally found a rather clear distinction in the CO_2 concentrations between schools with balanced mechanical ventilation and schools with natural ventilation where airing took place by manual opening of windows, both in this and in subsequent studies in Danish schools [22,28].

5. Conclusions

Although the current study was subject to different limitations as discussed in the previous section, the results showed that pupils in schools with balanced mechanical ventilation or mechanical exhaust typically scored higher in the national test scheme compared with pupils in schools with natural ventilation by manual window opening.

Widespread measurements in Danish schools showed that the CO_2 concentration in the classrooms was in general high and often above 1000 ppm, which is the currently recommended limit for CO_2 concentration in indoor air. The CO_2 concentration in classrooms with balanced mechanical ventilation or mechanical exhaust was lower than in naturally ventilated classrooms that were aired mostly by manual opening of windows.

The present study supplements the results of earlier studies and provides additional arguments for better classroom air quality to enhance progress in learning. The study shows that adequate air quality in classrooms should be a major priority when building new or retrofitting existing schools.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.buildenv.2015.05.017.

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