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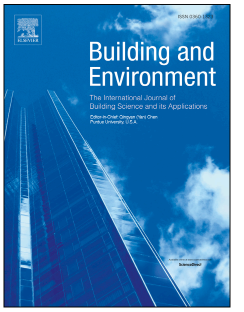

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Building characteristics, indoor environmental quality, and mathematics achievement in Finnish elementary schools

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Abstract

Objective: To study indoor environmental quality (IEQ) in elementary school buildings and its association with students' learning outcomes.

Methods: Measurements of ventilation rates and temperatures were recorded during school days in 108 classrooms in 60 schools in the spring and summer of 2007; background information on 3514 school buildings was retrieved from the Finnish population register. Data on school environment and students' health were collected by questionnaires from 4248 students as well as from 1154 school principals. Results from a national student achievement assessment program were used to assess learning.

Results: Upgrades to heating, ventilation, and air conditioning (HVAC) systems correlated significantly with airflow measurement, ventilation rate per student and per area, and mean temperature (r_s = 0.642, r_s = 0.654, r_s = 0.647 and r_s = -0.325 & r = 0.481, r = 0.483, r = 0.574, r = -0.271 respectively). The ventilation rate per student correlated with the number of students in classrooms (r_s = -0.360 & r = -0.387) and mean temperature (r_s = -0.333 & r = 0.393). Only schools with a mechanical supply and exhaust type of ventilation met the recommended ventilation rate per student of 6 *l/s* per person. An association was found between lower mathematics test results and schools that did not meet the recommended ventilation rate.

Conclusion: Ventilation is associated with thermal comfort and students' learning outcomes. The ventilation system requires scheduled maintenance or replacement as well as ongoing ventilation adjustment to accommodate the number of students at any one time.

Keywords: INDOOR ENVIRONMENT; SCHOOLS; HEALTH; LEARNING OUTCOMES; VENTILATION; THERMAL CONDITIONS

1. Introduction

Since children spend quality time in school trying to learn, it is important to study the effects of their classroom environment on their health and performance. Due to inadequate funding, the operations and maintenance of school facilities are often neglected and this leads to a persistence of environmental problems in schools [1], even while research has shown children to be more affected by indoor environmental quality (IEQ) compared to adults [2].

According to Zhao et al. [3], various pollutants such as bacteria, mould, volatile organic compounds (VOCs), allergens, and particulate matter (PM) can decrease indoor air quality (IAQ) in classrooms. VOCs can be emitted from materials used in the building construction or operation [4], mould and bacteria may grow due to dampness and moisture damage [5], while allergens and particulate matter (PM) may be brought into school by ventilation or students and staff. Interaction between these compounds can also alter IAQ [6].

Proper and adequate ventilation improves IAQ by diluting the concentration of pollutants present indoor, introducing fresh air from outdoors and removing polluted indoor air. Mechanical ventilation can be so-called mechanical exhaust ventilation, in which an amount of indoor air is continually extracted by the ventilation system, or mechanical supply and exhaust ventilation, in which the ventilation system continually introduces and removes an amount of air from the indoor environment [7]. Mechanical ventilation can also improve IAQ by bringing in filtered air, while direct ventilation by opening windows and doors can concurrently increase the amount of outdoor pollutants that enter indoors, especially in highly polluted urban areas [8, 9].

Several studies have reported associations between inadequate classroom ventilation and students' health and learning outcomes. Sundell et al. [10] found that reduced ventilation leads to asthma symptoms and lower respiratory functions, and Mendell et al. [11] related insufficient ventilation with students' absenteeism. Based on the literature, adverse health outcomes can be reduced by adequate classroom ventilation [12]. Recent studies have also reported associations between inadequate ventilation and learning outcomes [13-16]. In addition to improved IAQ, proper classroom ventilation could also improve thermal comfort [17, 18].

Classroom temperature is also important for students' performance [14, 19, 20]. Although it is difficult to define thermal comfort, it is generally accepted that 80% of occupants should be thermally comfortable in their environment [18], and it has been suggested that indoor temperature should always be below 24 ^{o}C in order to achieve thermal comfort for 85% of occupants [19].

The issues of low ventilation and thermal discomfort may be related to building characteristics and energy conservation. A poorly maintained school building may have its heating, ventilation, and air conditioning (HVAC) systems working below capacity [21], thereby leading to lower ventilation per student and/or per area. A low ventilation rate translates to low air flow, which may correspond with thermal discomfort in a hot season, especially if the building does not have cooling or air conditioning systems in place. Ventilation is sometimes purposefully reduced in order to decrease the need for heating or cooling. On the other hand, discomfort may occur during the cold season with a faulty or unadjusted heating system.

The European HealthVent project has proposed source control of ambient air by cleaning outdoor air that enters indoor ventilation (e.g. with periodical changes of HVAC filters) [22]. In addition, passive measures can also improve students' thermal comfort: elimination of radiant heat sources (such as printers in the classroom); installation of low-energy windows that reduce solar heat gain in warm weather and keep radiant heat inside in cold weather conditions without blocking outdoor views; the use of green roofing for insulation; as well as classroom furniture that discourage heat build-up and improve air movement [23, 24]. These passive methods should be preferred for controlling IAQ and thermal comfort, since they can help to conserve energy. Mechanical systems could be used as a last resort, when other methods fail and the expected benefits (for example improved student achievement) outweigh the potential costs. Knowledge is needed about the optimal level of HVAC operation while taking into account energy consumption, IEQ, and students' health and performance.

This study is a part of a broad research project that started in 2007 and has investigated Finnish elementary schools, their IEQ, and students' health and learning outcomes (Figure 1). Within the schools, the studies are focused on sixth grade students (mean age 12.5 years) and their classrooms.

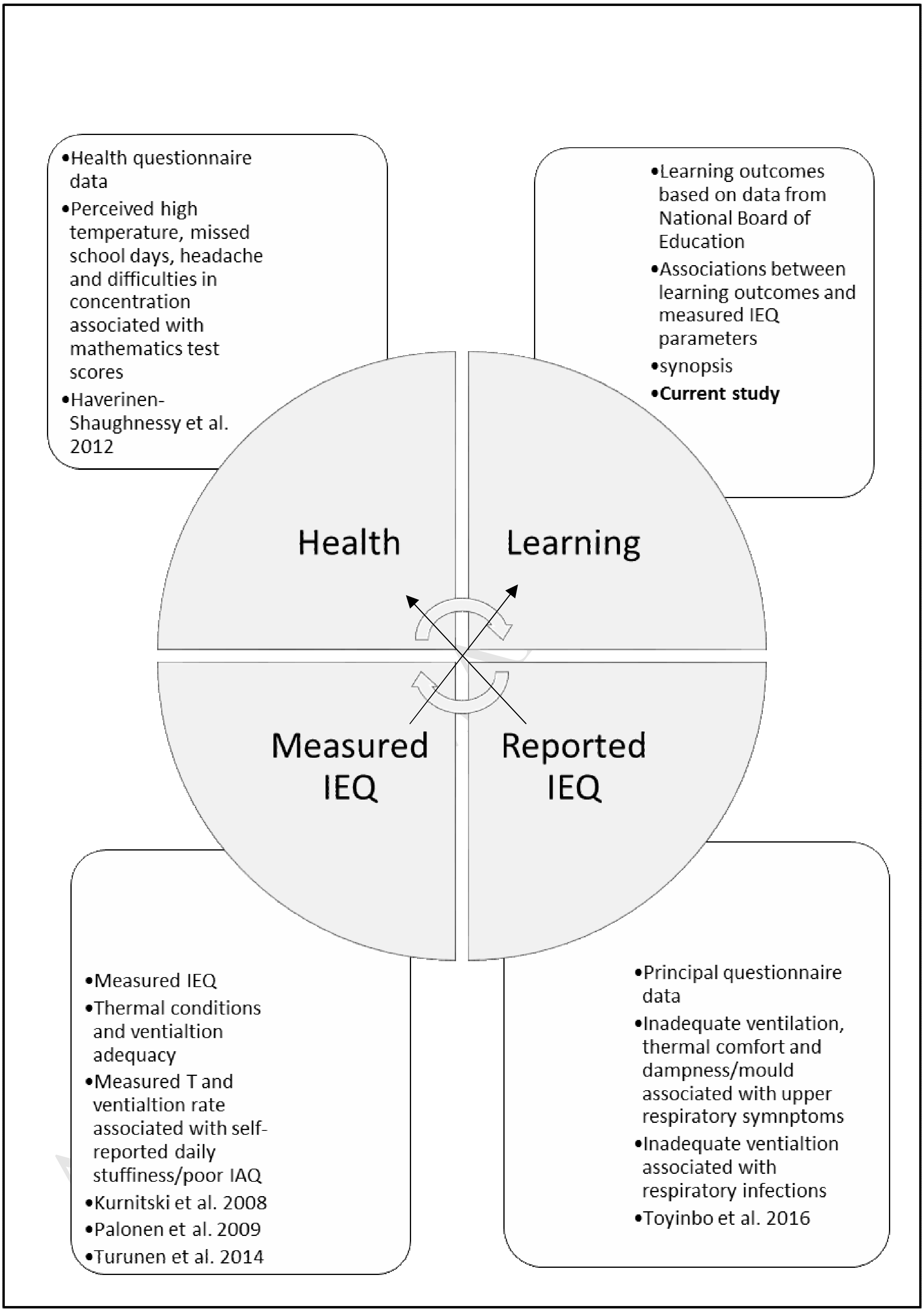

Figure 1. Conceptual diagram of the research project conducted in Finnish elementary schools 2007–2016.

The most recent study was focused on associations between IEQ, health, and building characteristics using data from student and principal questionnaires [25]. Other studies have assessed the school level prevalence of students' health symptoms [26], associations between students' health and learning outcomes [27], ventilation adequacy [21] and temperature control [28]. This paper focuses on associations between measured IEQ parameters and both building characteristics and learning outcomes, and forms a synopsis of the entire research project.

2. Materials and methods

2.1. Data collection

The database for the research project was described in Haverinen-Shaughnessy et al. [27]. Prior to data collection, the Institutional review board of the National Public Health Institute, Finland gave ethical approval for the study [25, 26]. Participation was voluntary.

Building characteristics such as building age, size, and type of ventilation and heating systems were retrieved from the Finnish population register center (FPRC). The FPRC had information about 3514 buildings out of a total of 3749 buildings, representing 2802 Finnish elementary schools (some schools occupy more than one building).

Questionnaires were sent to all Finnish elementary school principals in December 2007. Some principals are responsible for more than one school. A total of 2769 principals were identified, of which 1154 completed the questionnaire (response rate 42%). Some of the questions asked were about the school building condition and renovation, ventilation, thermal comfort, heating, and presence of dampness and mould.

A stratified random sample of 334 Finnish elementary schools participated in a national, 6th grade learning assessment of mathematics in March 2007 [29]. These schools, comprising

6787 students in the 6th grade, were also invited to participate in a questionnaire study about their school and home environment, health, and social economic status in May 2007. A total of 4248 students from 297 schools responded to the questionnaire (estimated response rate 63%). The students were encouraged to answer the questionnaire with their parents. Some of the questions asked students about their perception of their school's IEQ, such as the frequency (daily/weekly/occasionally/never) of perceived poor indoor air quality or high indoor temperature [25, 26]. Some other questions such as "Do you think your child is especially gifted or more advanced than other children of the same age *mathematically*?" were directed to the parents.

From the schools participating in the national learning assessment, 108 classrooms (serving 6th grade pupils) from 60 schools predominantly from Southern Finland were selected for further investigations and measurements. For the measurements, classrooms that had more than 15 students were selected (considered to have adequate sample size for statistical analyses).

Indoor temperatures were measured for several weeks in the spring and summer of 2007 (between March and June and August respectively). The measurements were conducted with Gemini Tinytag Plus data loggers (reading range -25°C to +85°C, resolution 0.01°C and accuracy 0.5 °C or better within the range of 0 °C to 40 °C). Daily average classroom temperatures were calculated using data from the school time period (from 8 am to 2 pm on weekdays). At the end of heating season, average outdoor temperature was 13.0°C (range 5.0 - 21.0°C), and it was 16.6°C (range 5.6-25.6°C) in the beginning of the school semester (right after the summer holidays in August). More detailed information about temperature measurements are reported by Kurnitski et al. [28].

From the same classrooms, ventilation rates were measured based on exhaust air flow or carbon dioxide (CO_2) measurements. The measurements were conducted during school days (normal occupancy conditions). In the classrooms with mechanical ventilation, exhaust air flow measurements were conducted on one occasion using a calibrated anemometer. (The prevailing ventilation system was a constant air volume system with constant supply air). In classrooms with natural (passive stack) ventilation, CO_2 measurements were made for five to ten days, based on which, the air change rate was estimated from tracer decay curves after the final school hour when classrooms were unoccupied [30]. More detailed information about ventilation rate measurements are reported by Palonen et al. [21].

2.2 Data analysis

IBM SPSS statistics version 21 was used to analyze the data. The data were preliminarily assessed using descriptive statistics related to building characteristics (e.g. data from FPRC), as well as data from the measurements (using school-level average or median values). Spearman's rho and Pearson correlations (together with their 95% confidence intervals) between building characteristics and the measured variables were calculated, together with effect sizes (Cohen's *d*). A test of correlation measures how related two sets of data are. The Pearson correlation shows the strength of any linear association between two normally distributed, independent variables, whereas Spearman's rho is used for variables that are not normally distributed [31]. Both correlation types have a range from +1 to -1, with a value greater than 0 indicating a positive relationship, those less than 0 indicating a negative relationship and a value of 0 showing no association between two sets of variables. A 95 % confidence interval gives a range of values that encompasses the actual population parameter in about 95 % of instances [31, 32]. An effect size (Cohen's *d*) shows the magnitude of the dependability (or correlation) between the variables. An effect size < 0.20 shows no effect (no correlation), 0.20 to 0.35 shows a small effect, 0.35 to 0.65 shows a medium effect, 0.65 to 0.80 shows a fairly large effect, and 0.80 or higher shows a large effect between groups

[33, 34]. The above methods have been used in several environmental health studies [13, 14, 32].

In addition, the associations between students' test results in mathematics and measured IEQ parameters in classrooms were studied using linear mixed modelling (LMM). The estimation was based on the Restricted Maximum Likelihood (REML) method and the Expected Maximum (EM) algorithm. The school and classroom codes were used as subject variables, and the covariance type was identity (covariance structure for a random effect with only one level). Only main effects are studied, while the factorial design with all interaction effects was not used.

First we studied a null model, which included only the outcome variable without any predictors, so as to examine the variance between student and school levels as well as to calculate the intra class correlation (ICC) (i.e. proportion of the total variance associated with differences among schools). Secondly, we selected socioeconomic status (SES) and background variables as the student-level covariates from a larger pool of variables selected for a LMM model fitted for mathematics achievement, as shown by Haverinen-Shaughnessy et al. [27]. Students' attitude towards mathematics was an additional variable obtained from the Finnish Education Evaluation Center (FINEEC), together with the results from mathematics tests. This variable was based on 15 statements on a 5-point Likert-scale centralized around 0 (-2 - +2) [29]. Next, the number of variables was reduced based on the Akaike information criterion (AIC), which is a measure of the relative quality of statistical models for a given set of data, considering that the number of schools and students in the sub-sample of measured schools was smaller as compared to the number of schools and students participating in a national mathematics testing and questionnaire study. Finally, IEQ indicators (ventilation rate and thermal conditions) were fitted to the model.

3. Results and discussion

Table 1 shows a summary of data retrieved from the FPRC (all schools) and those measured (60 schools). Information from the FPRC include year of construction, number of floors, and floor area. The rest of the data were from on-site investigation of the school buildings. Based on the FPRC data, the average year of construction was 1957 and the floor area was 2098 m^2, whereas the corresponding numbers for measured schools are 1967 and 3116 m^2, i.e. the measured schools are about 10 years newer and 30% larger, possibly related to their predominant location near larger municipalities with growing populations.

Table 1. Descriptive statistics of all Finnish elementary schools and a sub-sample of 60 schools with measurement data from 2007.

	All schools N = 2802		Measured schools N=60				
Attribute	Mean	Median	Mean	Median	SD	Min.	Max
Schools							
Year constructed	1957	1958	1967	1971	23.8	1875	2001
Floor area (m^2)	2098	1152	3116	3414	2060	100	8730
Number of floors	1.7	2.0	1.9	2.0	0.9	1.0	4.0
Volume (m^3)	-	-	12743	13460	8439	600	36677
HVAC upgraded (year)	-	-	1986	1998	22	1914	2006
Classrooms	-	-	N=108				
Number of students	-	-	24.0	24.0	5.3	8.0	47.0
Floor area (m^2)	-	-	61.0	60.0	9.2	40.0	99.0
Room height (cm)	-	-	319.5	320.0	23.2	265.0	385.0
Airflow design (*l*/s)	-	-	166.4	173.5	50.8	56.0	400.0
Airflow measurement (*l*/s)	-	-	127.9	125.0	70.7	30.0	400.0
Ventilation/m^2 (*l*/s/m^2)	-	-	2.2	2.0	1.1	0.5	5.0
Ventilation per student (*l*/s/student)	-	-	5.7	4.7	3.8	1.0	20.0
Mean temperature (^oC)	-	-	22.4	22.3	1.0	20.4	24.5
Max. temperature (^oC)	-	-	23.7	23.5	1.2	21.4	28.3

Min. temperature (^oC)	-	-	21.2	21.2	1.1	18.7	23.5

The average year of HVAC upgrade in the measured schools was 1986 (range from 1914 to 2006). In the event that the ventilation system had not been upgraded, the year corresponded with the original system installation. The mean number of students was 24 (range 8–47) and mean temperature (during school hours) was 22.4 °C (20.4–24.5 °C). Mean airflow was 127.9 (range 30.0–400.0) *l/s*, and ventilation rate per area was 2.2 (0.5–5.0) *l/s* per m^2, whereas ventilation rate per student was 5.7 (1-20) *l/s* per person.

Finnish children start school (grade 1) at age 7 years [35]. Most of the 6th grade students had been in the same school since the 1st grade, and the number of boys and girls was nearly equal (47% boys and 53% girls) with an average age of 12.5 years. The classroom height and net area complied with the National Building Code of Finland (NBCF) regulations for habitable rooms, which stipulates 250 cm and 7m^2 as the minimum height and floor area for habitable rooms respectively [36].

The difference of 38.5 *l/s* between mean airflow as designed and measured may mean that ventilation systems are not functioning properly [37]. Indeed, it was estimated that between 25 and 30 % of the schools studied have a ventilation system working below optimal performance and were in need of renovation or outright replacement [21]. A reduced airflow will possibly translate to a lower ventilation rate. This may be why the average ventilation rates per area and per student and ventilation per m^2 are lower than the standards of 3 *l/s* per m^2 or 6 *l/s* per person, respectively [36].

Based on the temperature measurements, the observed range was within 4 ^oC. None of the classrooms had temperatures below 18 ^oC, which is considered the lowest acceptable indoor temperature in Finland [38, 39]. The maximum temperature was 28 ^oC, which could have been due to outdoor conditions. In Finland, this can happen for a very limited and short period compared with some other countries in which this temperature or higher can last for somewhat longer periods, both day and night. Based on mean temperatures, about 25 % of classrooms had temperatures higher than 23 ^{o}C and about 10 % had temperatures higher than 24 ^{o}C. While these results concur with the results from the principal questionnaire, with 18 % reporting temperatures being too high outside the heating season, the results are anyhow rather inconclusive, due to the timing and duration of the measurements.

Spearman's rho and Pearson correlations as well as the effect size (Cohen's *d*) between background (e.g. those from FPRC) and measured variables are presented in Tables 2 and 3, respectively. Classroom volume was associated with mean temperature, while airflow measurement, ventilation rates, and mean temperature have significant correlations with the year of HVAC upgrade. This indicates the need for regular adjustment, maintenance, upgrade and/or replacement of faulty HVAC systems.

Table 2. Spearman's rho correlation between building characteristics and the measured variables.

	No. of students				Air flow measurement				Ventilation/m^2				Ventilation rate/student				Mean temperature			
	r_s	95%CI	*Sig.*	*d*	r_s	95%CI	*Sig.*	*d*	r_s	95%CI	*Sig.*	*d*	r_s	95%CI	*Sig.*	*d*	r_s	95%CI	*Sig.*	*d*
1	-.15	-.42–.15	.33	.29	.64**	.43–.79	.00	1.68	.65**	.44–.79	.00	1.70	.65**	.45 –.80	.00	1.73	-.33*	-.57– -.03	.03	.69
2	.09	-.22–.38	.57	.18	-.26	-.53– .05	.10	.55	-.23	-.51–.09	.15	.48	-.30	-.56– -.02	.06	.62	.11	-.22–.41	.52	.22
3	.22	-.09–.49	.16	.45	-.00	-.31–.31	.99	.00	-.06	-.25–.37	.71	.12	-.08	-.38–.24	.62	.16	-.23	-.51–.10	.17	.47
4	.23	-.10– .51	.17	.47	.10	-.23–.41	.56	.20	.18	-.16–.48	.29	.36	.00	-.32–.33	.99	.01	-.36*	-.62–-.03	.04	.77
5	-.04	-.35–.28	.80	.08	.09	-.24–.40	.60	.18	.169	-.16–.47	.32	.34	.11	-.22–.42	.52	.22	-.04	-.37–.30	.81	.08

* *Correlation is significant at the 0.05 level (2-tailed).*

** *Correlation is significant at the 0.01 level (2-tailed).*

(1 = HVAC upgrade, 2 = Number of floors, 3 = Floor area, 4 = Volume and 5 = Year of construction)

Table 3. Pearson correlation between building characteristics and the measured variables.

	No. of students				Air flow measurement				Ventilation/m^2				Ventilation rate/student				Mean temperature			
	r	95%CI	*Sig.*	*d*	*r*	95%CI	*Sig.*	*d*	*r*	95%CI	*Sig.*	*d*	*r*	95%CI	*Sig.*	*d*	*r*	95%CI	*Sig.*	*d*
1	-.10	-.38–.19	.49	.21	.48**	.22–.68	.00	1.10	.57**	.34–.74	.00	1.40	.48**	.22–.68	.00	1.10	-.27	-.53–.03	.08	.56
2	.11	-.20–.40	.48	.23	-.26	-.53– -.06	.11	.53	-.18	-.47–.14	.26	.37	-.23	-.50–.09	.16	.47	.09	-.24–.34	.58	.19
3	.09	-.22–.39	.56	.19	-.04	-.34–.28	.83	.07	.04	-.27–.35	.80	.08	-.08	-.38–.24	.64	.16	-.28	-.55–.05	.09	.58
4	.11	-.22–.41	.51	.22	.04	-.29– .36	.82	.08	.12	-.22– .42	.50	.23	-.01	-.34– .31	.95	.02	-.38*	-.64– -.05	.03	.82
5	-.09	-.39–.23	.59	.18	.03	-.30– .35	.22	.05	.11	-.23– .42	.54	.21	.01	-.31– .34	.93	.03	-.20	-.50– .15	.26	.40

* *Correlation is significant at the 0.05 level (2-tailed).*

** *Correlation is significant at the 0.01 level (2-tailed).*

(1 = HVAC upgrade, 2 = Number of floors, 3 = Floor area, 4 = Volume and 5 = Year of construction)

In addition, there is a negative significant correlation between the number of students and ventilation rate per student (r_s = -0.360, p < 0.008, d = 0.771 & r = -0.387, p < 0.004, d = 0.839), as well as between ventilation rate per student and mean temperature (r_s = -0.333, p = 0.018, d = 0.706 & r = -0.393, p = 0.005, d = 0.855).

The data were further analyzed based on ventilation system type: 1) mechanical ventilation, including both mechanical supply and exhaust ventilation and mechanical exhaust only and 2) natural (passive stack) ventilation. The results for mechanical ventilation still show a significant negative correlation between number of students and ventilation rate per student (r_s = -0.441, p = 0.002, d = 0.983 & r = -0.432, p = 0.002, d = 0.958) and also between ventilation rate per student and mean temperature (r_s = -0.316, p = 0.014, d = 0.666 & r = -0.413, p = 0.004, d = 0.907). For naturally ventilated classrooms, there was no statistically significant correlation between ventilation rate per student and number of students (r_s = -0.232, p = 0.658, d = 0.477 & r = -0.619, p = 0.190, d = 1.57) or the mean classroom temperature (r_s = -0.400, p = 0.600, d = 0.873 & r = -0.319, p = 0.681, d = 0.673). This is probably because only a small number of schools (seven schools with 18 classrooms) relied on natural ventilation. However, Cohen's d values denote medium to large effects between the variables. These results indicate that regular ventilation adjustment is required to meet classroom population at any given time, while discouraging overcrowding.

From another perspective, there is a significant correlation between student's daily perception of poor air quality in the classroom and both mean temperature (r_s = 0.409, p = 0.004, d = 0.896 & r = 0.343, p = 0.017, d = 730) and ventilation rate per student (r_s = -0.300, p = 0.029, d = 0.629 & r = -0.306, p = 0.026, d = 0.643). It appears that low ventilation is related to both perceived poor air quality and high indoor temperature, which has also been reported in other studies [17, 26, 40].

As shown in Table 4, there are differences in the estimated ventilation rates by the type of ventilation system. The ventilation rates per student were below the recommended level of 6 *l/s* per person in all schools with mechanical exhaust or passive stack ventilation, and were exceeding the recommended level only in 52% of schools (44 out of 84 classrooms) with a mechanical supply and exhaust ventilation system.

Table 4. Ventilation rates by type of ventilation system in classrooms.

Type of ventilation	Mechanical supply and exhaust (n=84)		Mechanical exhaust (n=6)		Natural ventilation (n=18)	
	Ventilation rate (*l/s*)		Ventilation rate (*l/s*)		Ventilation rate (*l/s*)	
	/m^2	/student	/m^2	/student	/m^2	/student
Mean	2.4	6.5	1.2	3.0	1.1	3.0
Median	2.4	6.1	1.3	3.2	1.1	3.0
SD	1.1	3.9	.6	1.8	.3	.9
Minimum	.5	1.2	.5	1.0	.7	1.8
Maximum	5.0	20.0	1.7	4.6	1.5	4.7

Based on the LMM models, school explains about 15 % of the total variance (ICC = .15) in the mathematics test result and school * classroom explains 17%. By including student background variables as fixed effects, the variance component within subjects diminishes by 67% and the variance component between subjects diminishes by 32%, while school * classroom explains 23% of the remaining variance. By including the continuous classroom ventilation rate and temperature variables as fixed effects, estimates (95%CI) are 0.1 (-0.4 - 0.7) for the ventilation rate and -0.3 (-2.2 - 1.6) for temperature, i.e. small and statistically non-significant. However, preliminary analyses suggested significantly lower mathematics test results in schools where the ventilation rate was lower than the recommended value of 6 *l/s* per person. This association is statistically significant (Table 5), and by including the dichotomized ventilation rate variable, ICC is reduced to .21, which corresponds to a 9% reduction in the variance component between subjects (i.e. school * classroom). We also ran the model for schools with mechanical supply and exhaust ventilation, which were the only schools exceeding the recommended level. The results are comparable, indicating that the association is not confounded by the type of ventilation system.

Table 5. Linear mixed model for % of correct answers in mathematics test, including students' attitude, statistically significant SES and background variables, as well as 2-category classroom ventilation rate (based on measurements) and thermal comfort (self-reported).

	All students	Sub-sample	Estimates for fixed effects		
	N=4248	N=1055	Estimate	95%CI	p
	Mean[a]	Mean[a]			
Attitude towards mathematics	0.54	0.62	8.5	6.9-9.4	0.000
	%[b]	%[b]			
First language Finnish	90.4	96.0	11.9	7.2-16.5	0.000
Swedish	7.4	0.3	8.2	-7.6-23.9	0.309
Other	2.2	3.7	0[c]		
Mother's education primary school	10.5	11.4	-5.4	-(8.6-2.1)	0.001
high school / equivalent	36.1	29.6	-4.9	-(7.1-2.7)	0.000
college / university	53.4	59.0	0[c]		
Father's education primary school	17.9	14.9	-6.8	-(9.8-3.8)	0.000
high school / equivalent	45.0	36.0	-3.1	-(5.2-1.0)	0.004
college / university	37.1	49.1	0[c]		
Takes naps during the day	10.7	10.8	-3.7	-(0.9-6.4)	0.010
Gifted in mathematics[d, e]	18.4	20.5	11.8	9.4-14.1	0.000
Gifted linguistically[d,e]	20.5	22.4	5.7	3.6-7.9	0.000
Gifted in sports[d,e]	22.9	25.9	-2.6	-(4.6-0.6)	0.012
Needs personal tutoring regularly[d]	8.3	7.6	-14.3	-(10.9-17.7)	0.000
High indoor temperature daily[d]	3.0	3.7	-4.8	-(0.4-9.2)	0.034
Ventilation rate <6 *l/s* per person[f]	-	61.8	-3.6	-(7.0-0.2)	0.040

[a] Mean value referring to students' attitude towards mathematics on a continuous scale -2- +2
[b] Percent of students with the following attributes
[c] This parameter is set to zero because it is redundant
[d] Based on questionnaire data
[e] Questions formulated as follows: "Do you think your child is especially gifted or more advanced than other children of the same age *mathematically*?"
[f] In schools with mechanical supply and exhaust, the corresponding estimate is -3.6, 95%CI -(7.2 - 0.1), p = 0.047

It should be noted that both methods used for estimating ventilation rates (including an estimation based on air flow measurements and CO_2 concentrations) entail some uncertainties. Air flow measurements probably underestimate the actual ventilation rate, which in reality is increased by opening windows and doors as well as air leakage through the building envelope. Estimation based on CO_2 decay may also lead to underestimating the actual ventilation rate, since after school hours, windows and doors are more likely to be closed than during school days. In addition, the measurements were done in each school during the spring term; therefore we could not evaluate the effect of seasonal variation in detail. Seasonal variation could be greater in schools with passive stack ventilation, which is more dependent on outdoor temperatures, as well as other conditions such as wind direction and velocity.

Indeed, uncertainty related to the ventilation rate estimates may be the most limiting factor for drawing more definite conclusions on the ventilation adequacy and its associations with learning outcomes: further studies are recommended with longer follow-up periods and continuous (real-time) monitoring during normal occupancy situations throughout the school year. A larger sample size would also give more statistical power for performing more detailed analyses and modelling of the associations. However, in practical terms it appears that ventilation rates in classrooms should meet the required minimum of 6 *l/s* per person. It also appears that mechanical exhaust and the passive stack type of ventilation systems may not be able to provide adequate ventilation for classrooms in the Finnish climate throughout the year. Based on the results related to learning outcomes, this study did not indicate a need to increase the ventilation rate above the current standards in Finnish schools, since we did not find a continuous, linear association between ventilation rate and mathematics test results.

The potential to reduce the ventilation rate should also be considered for energy conservation purposes; however, it would require more information about actual indoor air pollutants, as ventilation is merely an indicator of IAQ. Future studies could benefit from utilizing multi-pollutant assessment to thoroughly characterize IAQ in schools, which would improve understanding of the children's exposure to indoor air pollutants and the most effective means to reduce these exposures. Such studies have also been useful in terms of developing strategies (such as source control) for preventing adverse health consequences for children in schools [41, 42].

Whereas mean indoor temperature was not associated with mathematics test results, we have previously found an association between math test results and students' reporting too high temperature daily [27]. While the percentage of students reporting daily discomfort is only 4%, this association remained significant also in the LMM model including the 2-categorical ventilation rate. Therefore, it appears that in these data, subjectively perceived temperature is related to mathematics achievement. It was noticed that of those students who perceived too high indoor temperatures daily, some 42% had a classroom temperature >23 ^{o}C, whereas 74% had a classroom ventilation rate of <6 *l/s* per person. A possible explanation is that the mean indoor temperature during our measurement period (spring semester) was not representative of the temperature during the recall period used in the questionnaire (i.e. 12 months). Another explanation is that the students' perception of high temperature in our data could be related to the low ventilation rate rather than to high temperature. Although the data for this study only allowed us to compare perceived thermal comfort with the measured ventilation rate and temperature, further studies should compare perceived temperature with contemporaneous thermal environmental conditions, such as relative humidity, air velocity, and radiant heat.

In summary, a broad research project involving Finnish elementary schools was carried out. Based on the previously published results, noise (11%) and stuffiness/poor IAQ (7%) in the classroom are the leading cause of daily discomfort as perceived by the students [26]. It was found that self-reported thermal discomfort (too high temperature daily), missed school days due to respiratory infections, headache, and difficulties in concentration was associated with mathematics test results [27].

Principals reported inadequate ventilation (38%), dampness or moisture damage (27%), and unsatisfactory temperatures (11-18%) in schools [25]. We found that these school-level IEQ indicators could explain a large part of the school-level variations observed in self-reported upper respiratory symptoms among students. In addition, a higher number of missed school days due to respiratory infections were found in schools in which inadequate ventilation had been reported by the principal. The current study completes the research project by reporting results from combined analysis based on data from objective measurements as well as national assessment of mathematics.

4. Conclusions

Based on the current study, ventilation rate per area and per student were below standard in a majority of the classrooms measured (67% and 58 % respectively). The standard was not met in any of the classrooms with passive stack ventilation or with mechanical exhaust only: in these cases, ventilation systems may need adjusting, maintenance, or upgrading. In addition, adjustment of the ventilation rate should always be done to accommodate the maximum number of students at any given time. Adequate ventilation is also related to thermal comfort and appears to be associated with mathematics test results, which emphasizes the importance of meeting standards. Based on the results related to learning outcomes, this study did not indicate a need to increase the ventilation rate above the current standard in Finnish schools. However, further studies with more schools and longer follow-up periods are recommended for more in-depth assessment.

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Competing interests

Authors declare no conflict of interest.

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- Based on a large dataset involving Finnish elementary schools, 6th grade students in classrooms fulfilling the required ventilation rate of 6 l/s per person had significantly higher mathematics test results as compared to students in classrooms failing the national standards.
- Ventilation rates were also associated with both perceived air quality and thermal comfort among students.
- Some 52% of the classrooms with both mechanical supply and exhaust air fulfilled the current standards, whereas all classrooms with mechanical exhaust or natural ventilation failed.
- Other factors related to ventilation adequacy were HVAC upgrade and number of students in classrooms. For schools failing the guidelines, upgrading the ventilation system and / or reducing class sizes may be necessary.
- The results did not indicate a need to increase ventilation rate above the current standards.