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THE VENTILATION PROBLEM IN SCHOOLS: LITERATURE REVIEW

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ABSTRACT

Based on a review of literature published in refereed archival journals, ventilation rates in classrooms often fall far short of the minimum ventilation rates specified in standards. There is compelling evidence, from both cross sectional and intervention studies, of an association of increased student performance with increased ventilation rates. There is evidence that reduced respiratory health effects and reduced student absence are associated with increased ventilation rates. Increasing ventilation rates in schools imposes energy costs and can increase HVAC system capital costs. The net annual costs, ranging from a few dollars to about ten dollars per person, are less than 0.1% of typical public spending on elementary and secondary education in the US. Such expenditures seem like a small price to pay given the evidence of health and performance benefits.

Keywords: carbon dioxide, costs, health, performance, schools, ventilation

Practical Implications

Increasing ventilation rates in schools to meet or exceed the rates specified in standards is likely to improve student health and performance and can be accomplished with incremental energy and capital costs that are very small relative to spending on public school education.

INTRODUCTION

In this paper, the term ventilation refers to the supply of outdoor air to a building. Ventilation in schools can be provided mechanically using fans and/or naturally through leaks in the building envelope and as a consequence of natural airflows through open windows and doors.

Rates of ventilation in schools, and in other buildings, influence indoor air pollutant concentrations. Based on mass balance considerations, indoor air concentrations of pollutants emitted from indoor sources decrease as ventilation rates increase and indoor air concentrations of some pollutants from outdoor air such as ozone and outdoor air particles will increase as ventilation rates increase. Ventilation rates also affect the energy required for heating and cooling, with higher ventilation rates generally increasing energy requirements when a space is being heated or air conditioned[1-4]. The increase in energy consumption with increased ventilation rate will vary with climate and with building and HVAC characteristics. Sometimes, increased ventilation can save energy, when conditions enable use of cool outdoor air to reduce the need for air conditioning. In schools without air conditioning, ventilation is commonly employed during periods of warm weather to limit indoor temperatures. Heat is generated by the occupants and equipment in schools and ventilation is used to remove that heat and help maintain tolerable indoor temperatures. The energy consumed by school HVAC systems includes the energy consumption attributable to heating, cooling, and dehumidification of ventilation air and the energy consumption attributable to other processes, such as heat conduction through buildings envelopes. The portion of heating, ventilating, and air conditioning (HVAC) system energy use attributable to ventilation cannot normally be directly measured; thus, mathematical models of building energy performance have been employed to predict energy consumption and energy costs with and without ventilation or with different rates of ventilation.

Minimum ventilation rate standards have been established, seeking to strike a balance between effects of decreasing ventilation on air quality and energy use[5, 6]. Standards for school classrooms often specify a minimum ventilation rate per person and/or a minimum ventilation rate per unit floor area. A commonly used minimum ventilation standard in the U.S. specifies a minimum ventilation rate for classrooms of approximately 7 liters per second (L/s) or 15 cubic feet per minute (cfm) per occupant at the default occupant density[5]. A European standard specifies a minimum ventilation rate of 8 L/s (17 cfm) per occupant for moderate indoor air quality and 12.5 L/s (29 cfm) per occupant for medium indoor air quality[6].

Carbon dioxide (CO_2) concentrations are often used as an easily measured proxy for ventilation rates. When an indoor space is unoccupied and there is air entering from outdoors, the indoor concentration of CO_2 approaches and eventually equals the outdoor concentration. When people enter the space, indoor concentrations increase over time because people are a source of CO_2. If the number of occupants and the amount of ventilation is consistent over a sufficient period of time, the indoor CO_2 concentration will reach a steady value that depends on the amount of ventilation per person[7]. Even though steady concentrations are not always reached, it is possible to use the “peak” or highest measured concentration to indicate if a ventilation standard is being met. Peak indoor CO_2 concentrations above approximately 1000 parts per million (ppm) indicate ventilation rates less than 7 L/s (15 cfm) per occupant.

In hot and humid climates, increased ventilation rates in schools can increase time periods with an elevated indoor humidity, increasing the risk of indoor mold growth. This concern arises, in particular, with a typical heating, ventilating, and air conditioning (HVAC) configuration in which the cooling coil is placed in the mixture of outdoor air and recirculated indoor air. Even with low ventilation rates, indoor humidity is often elevated in high humidity climates but this problem can be exacerbated when ventilation rates are increased[4]. Several HVAC configurations can reduce periods of elevated indoor humidity and sometimes also save energy[4], but impose higher equipment costs.

This document provides a review of published literature on ventilation of schools, with the primary focus on school classrooms. Topics addressed include the ventilation rates and CO_2 concentrations measured in schools, their associations with the health and performance of occupants, and their influence on energy use or energy costs.

METHODS

Papers on ventilation rates and CO_2 concentrations and their associations with occupant health and performance were identified via searches using PubMed and Google Scholar. Search terms included various combinations of school, classroom, ventilation, carbon dioxide, CO_2, indoor air quality, IAQ, health, allergy, asthma, sick building syndrome, absence, sick leave, performance, productivity. Papers on the extent to which ventilation affects energy use and energy costs were identified via a search using Google Scholar with combinations of school, classroom, ventilation, and energy as search terms. Titles and abstracts were read to determine a paper's relevance, and relevant papers were fully reviewed. Additional papers were identified in the reference sections of papers identified via these web-based searches. Papers not published in refereed archival journals and previous literature reviews were excluded from consideration, except due to the limited refereed archival literature on the energy impacts of ventilation, one report[1] addressing that topic was also considered. Ventilation rate and CO_2 data were only used if those data reflected periods of occupancy. Some papers provided estimates of the energy impacts of ventilation but did not estimate energy costs. In these instances, energy costs were calculated, when possible, using average commercial energy prices in the U.S. in January 2017 from the U.S. Energy Information Administration[8, 9]. These prices were $0.109 per kWh for electricity and $0.025 per kWh of thermal energy content ($0.069 per MJ) for natural gas. Several identified papers addressed the associations of occupant health outcomes with type of mechanical ventilation system; however, this issue was not reviewed. To facilitate a synthesis of published information, tables of study characteristics and study findings were prepared, and plots were developed of some findings. Conclusions reflected consistency of findings, numbers of studies with consistent findings, and indicators of study quality such as study size and extent of control for potential confounders.

RESULTS

Carbon Dioxide Concentrations and Ventilation Rates in Schools

Figure 1 plots peak values of CO_2 concentration measured in classrooms from studies with 20 or more classrooms. The plot only includes data from measurements when classrooms were occupied or measurements characterized as during the school day. Study information is provided in Table 1. When available, the figure shows the reported average, median, and maximum value of the peak CO_2 concentrations measured in the set of classrooms within the study. In all studies, the reported average and median values of the peak CO_2 concentration exceeded 1000 ppm, and in many instances 2000 ppm was exceeded. Also, the maximum peak CO_2 concentrations range from about 3000 to 6000 ppm. Figure 2 shows time-average, as opposed to peak, CO_2 concentrations, also from studies with 20 or more classrooms. A majority of the averages and medians of time-average concentrations also exceeded 1000 ppm with maximum values ranging from 1400 ppm to 5200 ppm. Concentrations of CO_2 do not appear to be systematically higher or lower in naturally ventilated classrooms relative to mechanically ventilated classrooms. These CO_2 data indicate a widespread failure to provide the minimum amount of ventilation specified in standards for classrooms. The finding that CO_2 concentrations often far exceed 1000 ppm indicates that ventilation rates are often far less than 7 L/s (15 cfm) per occupant. Several of the studies within Table 1 provide ventilation rates and these rates are included in Table 1. The ventilation rates were estimated based on peak CO_2 concentrations unless the table indicates otherwise. Consistent with the high reported CO_2 concentrations, many studies report average or median ventilation rates in the range of 3 to 5 L/s (6 to 11 cfm) per occupant, with one average as low as 1 L/s (2 cfm) per occupant.

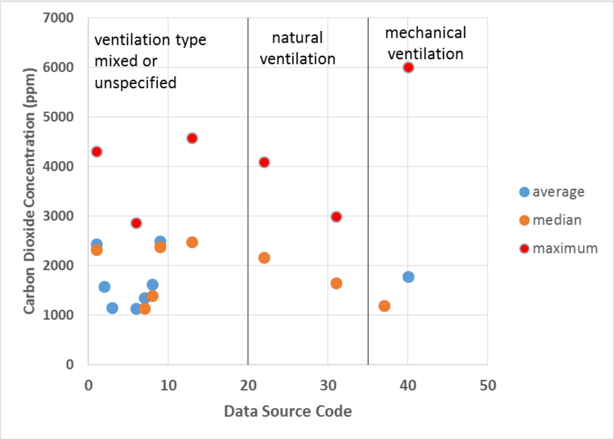

Figure 1. Peak carbon dioxide concentrations in classrooms.

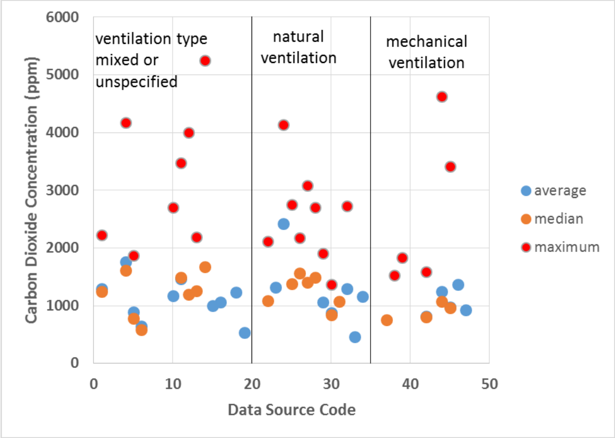

Figure 2. Time average carbon dioxide concentrations in classrooms.

Table 1. Carbon dioxide concentrations and ventilation rates in schools from studies with measurements during occupancy in 20 or more classrooms.

Location **Grade Levels**	**Number of Classrooms (CRs) And Schools (S)** **Ventilation Type** **NV= natural** **MV = Mechanical**	**Measurement Period(s)**	**Data Source Code** **Reported carbon dioxide (CO_2) concentrations in ppm and ventilation rates (VRs) in L/s (cfm) per occupant** **[A = average, SD = standard deviation, M = median, Min = minimum, Max = maximum]**	**Refer-ence**
France Nursery and Elementary	51 CRs 17 S NV: 37 CR MV: 14 CR	8:00 am – 5 pm, M-F for one week VRs determined from CO_2 buildup curve	1 Time Average CO_2: A 1290 SD 400 M 1250 Min 530 Max 2220 1 Peak CO_2: A 2440 M 2320 Min 580 Max 4310 1 VRs: A 2.9 (6.1) SD 1.6 (3.4) Min 0.6 (1.3) Max 8.2 (17.4)	[10]
Portugal Grade 1-4	81 CR 51 S Ventilation type not specified	typically two 30 min. measurements per day ~ 2 h after start of class, morning and afternoon	Peak CO_2: 2 A 1578 SD 712 Fall/winter 3 A 1153 SD 595 Spring/summer	[11]
Germany Primary and Secondary	90 CR in winter and 75 CR in summer 64 S NV: 62 S MV: 2 S	5 h of on single day in each CR	Time average CO_2: 4 A 1759 M 1608 Min 598 Max 4172 winter 5 A 890 M 785 Min 480 Max 1875 summer	[12]
Scotland Primary	60 CR 30 S NV: 60 CR	during occupancy over 3 – 5 school days per CR	6 Time average CO_2: M 1086 Min 592 Max 2115 6 Peak CO_2: M 2167 Min 1065 Max 4093	[13]
Netherlands Primary	81 CR 20 S NV: 81 CR	every 3 minute in school day	7 Time average CO_2 (before interventions): A 1323	[14]
United States Elementary and Middle	47 CR 9 S MV: 47 CR	occupied rooms over 4.5 day period in most S	8 Time Average CO_2: M 750 9 non portable CR: Min: 533 Max 1522 10 portable CR: Min 1148 Max 1836 8 Peak CO_2: M 1200	[15]
United States 5th Grade	100 CR 100 S MV: 100 CR (MV fan operated continuously)	during occupied hours minimum of 1 day per CR	Peak CO_2: 11 A 1779 SD 852 Min 661 Max 6000 VRs: 11 A 4.2 (8.9) SD 2.3 (4.9)	[16]
United States 5th Grade	140 CR 70 S MV: 140 CR	during occupied S hours (duration may be 1 week per CR)	VRs 12 A 3.6 SD 2.3 Note: data may overlap with data in prior row of this table	[17]
Korea 4th Grade	34 CR 12 S NV: 34 CR	45 to 60 minute per CR, time of day not specified	13 Time average CO_2: A 2417 SD 839 Min 907 Max 4113	[18]
Denmark Day Care	20 Day care centers NV: 2 centers MV: 18 centers	continuously during occupancy, measurement days not specified	14 Time average CO_2: A 643 M 579 14 Peak CO_2: A 1132 Min 681 Max 2864	[19]

Table 1. continued

Location Grade Levels	Number of Classrooms (CRs) And Schools (S) Ventilation Type NV= natural MV = Mechanical	Measurement Period(s)	Data Source Code Reported carbon dioxide (CO_2) concentrations in ppm and ventilation rates (VRs) in L/s (cfm) per occupant [A = average, SD = standard deviation, M = median, Min = minimum, Max = maximum]	Refer-ence
United States Grades 3 - 5	162 CR 28 S 3 school districts NV: 60- CR MV: 102 CR	continuously for approximately 2 year in each CR	Peak CO_2: 15 District 1 (59 CR): A 1350 SD 652 M 1140 16 District 2 (52 CR): A 1630 SD 770 M1400 17 District 3 (51 CR): A 2490 SD 901 M 2380 VRs: 15 District 1 (59 CR): A 8.4 (17.8) SD 5.5 (11.7) M 7.0 (14.8) 16 District 2 (52 CR): A 6.2 (13.1) SD 4.0 (8.5) M 5.1 (10.8) 17 District 3 (51 CR): A 3.1 (6.6) SD 2.0 (4.2) M 2.6 (5.5)	[20]
Portugal Day Care	52 CR 9 day care centers NV: 52 CR	at least 4 h starting at 9:00 am	[1]Time Average CO_2: 18 Nursery CR Spring: M 1377 Min 973 Max 2750 19 Nursery CR Winter: M 1563 Min 687 Max 2178 20 Kindergarten CR spring: M 1402 Min 351 Max 3087 21 Kindergarten CR Winter: M 1492 Min 507 Max 2706	[21]
China Junior high	30 CR 10 S NV: 30 CR	1 h during occupancy	22 Time average CO_2: A 1060 SD 370 Min 530 Max 1910 22 VRs: A 8.8 (18.6) Min 2.6 (5.5) Max 21.7 (46.0)	[22]
United States Elementary and middle/high	64 CR 10 S MV: 64 CR	over 48 h during 2 days with occupancy	23 Time average CO_2: A 812 SD 215 M 799 Min 352 Max 1591	[23]
Sweden Primary	36 CR 6 S NV: 12 CR MV: 24 CR	5 – 10 min at the end of lectures	24 Time average CO_2: A 1177 Min 700 Max 2700	[24]
Italy Primary and Secondary	21 CR 7 S NV: 21 CR	5 days during CR occupancy in each of 2 years	25 Time average CO_2: A 881 SD 175 M 840 Min 567 Max 1370	[25]
Greece Grade levels not specified	62 CR 27 S NV: 62 CR	during teaching, duration not described VRs based on tracer gas method	26 Time average CO_2: M 1070 26 Peak CO_2: M 1650 Min 750 Max 3000 26 Ventilation rates: A 4.9 (10.4) M 4.5 (9.5) during teaching period	[26]
United States 5th Grade	54 CR 54 S MV: 54 CR	4 to 5 hours with windows closed and ventilation system operating	27 VRs: A 3.9 (8.3) Min 0.9 (1.9) Max 11.7 (24.8)	[27]
United States Elementary	434 CR 22 S MV: 434 CR	five minute measurement per CR at various times throughout school day	Time average CO_2 (adding 400 ppm to indoor-outdoor differences): 165 traditional CR in Idaho: 28 A 1240 SD 630 M 1070 Min 450 Max 4630 244 traditional CR in Washington State: 29 A 980 SD 310 M 970 Min 460 Max 3430	[28]
Europe Grade Levels not specified	46 CR 21 S Mix of NV and MV	minimum of 4 h during occupancy on one day	30 Time average CO_2: A 1467 SD 683 M 1490 Min 525 Max 3475 30 VRs: A 7.5 (15.9) SD 7.9 (16.7) M 3.1 (6.6) Min 1.5 (3.2) Max 35.0 (74.2)	[29]

Table 1. continued

Location Grade Levels	**Number of Classrooms (CRs) And Schools (S) Ventilation Type NV= natural MV = Mechanical**	**Measurement Period(s)**	**Data Source Code Reported carbon dioxide (CO_2) concentrations in ppm and ventilation rates (VRs) in L/s (cfm) per occupant [A = average, SD = standard deviation, M = median, Min = minimum, Max = maximum]**	**Refer-ence**
Denmark Pre-school to High School	820 CR 389 S Mix of NV and MV	in 732 CR, measured once briefly at end of a lesson; in 88 CR, measured over average of 17 days	Time average CO_2: 31 732 CR with spot measurements: M 1200 Min 400 Max 4000 32 88 CR with measurements over time: M 1261 Min 578 Max 2183 Peak CO_2: 32 88 CR with measurements over time: M 2479 Min 900 Max 4597	[30]
United States Elementary	385 rooms (5 – 7 CR and libraries) in each of 60 S Ventilation types not specified, some or all have MV	3 minutes per CR between 11:00 am and 3:00 pm	33 Time average CO_2: M 1672 Min 385 Max 5247	[31]
Germany Elementary	20 CR 6 S MV: 20 CR	over 4 h after start of classes, on 2 days per CR	34 Time average CO_2: A 1371	[32]
Sweden Primary and Secondary	100 CR 39 S Ventilation types not specified, some or all have MV	twice per CR for 165 minutes at the end of a lesson	Time average CO_2 — VRs 35 Baseline period A 998 SD 301 — A 5.4 SD 4.3 36 Follow up period A 1059 SD 345 — A 7.9 SD 4.8	[33]
Sweden Primary	24 CR 12 S NV: 8 CR MV: 16 CR S	measured VRs with tracer gas decay method	37 VRs: A 4.4 (9.3) Min 1.1 (2.3) Max 9.0 (19.1)	[34]
Korea Kindergarten through High	165 CR 55 S Ventilation type not specified	5 -7 h during occupancy on one day	38 Time average CO_2: A 1229 SD 799	[35]
China Jr. High	32 CR 10 S NV: 32 CR	2 h per CR during occupancy on 2 years	39 Time average CO_2: A 1290 SD 610 Min 428 Max 2728	[36]
Singapore Day Care	208 CR 104 daycare centers NV: 59 CR Hybrid ventilation: 21 CR MV with air conditioning: 5 CR NV with air conditioning: 19 CR	8 :00 am to 5:00 pm, number of measurement days not specified	Time average CO_2: 40 59 naturally ventilated CR A 466 SD 72 41 21 CR with hybrid ventilation A 538 SD 147 42 5 CR with MV and air conditioning A 930 SD 175 43 19 CR with NV and air conditioning A 1163 SD 575 VRs 40 59 NV CR A 16.4 (34.7) SD 29.5 (62.5) 41 21 CR with hybrid ventilation A 8.6 (18.2) SD 18.9 (40.0) 42 5 CR with MV and air conditioning A 1.0 (2.1) SD 1.6 (3.4) 43 19 CR with NV and air conditioning A 1.6 (3.4) SD 2.0 (4.2)	[37]

[1] based on method description, concentrations are assumed to be time average values

Associations of ventilation rates with health and performance

Table 2 provides summaries of studies of the associations of ventilation rates or CO_2 concentrations in schools with student performance, health symptoms or health signs, and absence rates. Key study features are included in the table including study size and the extent to which each study controlled for potential confounding.

Table 2 includes 11 studies of the associations of student performance with ventilation rates or CO_2 concentrations. In five of these studies, reported in six papers[13, 16, 17, 27, 38, 39], students' scores on standard academic achievement tests used by school districts were employed to assess student performance. In the remaining six studies[32, 40-44], special tests were added by the researchers to measure student performance. Overall, eight of the eleven studies report statistically significant improvements in at least some measures of performance with increased ventilation rates or lower CO_2 concentrations, while a ninth study[27] reported a statistically significant improvement when applying a less stringent than typical criterion for statistical significance ($P < 0.1$ was used while other studies used $P < 0.05$). A tenth study found general improvements in performance with increased ventilation rates that were not statistically significant[39]. Performance generally improved a few percent, to as much as 15%, with increased ventilation rate or with lower CO_2 concentration. Five of eleven studies were intervention studies[32, 40, 41, 43, 44] in which ventilation rates were increased and changes in performance within students were measured. These intervention studies employed special tests of aspects of student performance, such as speed and accuracy in number addition, multiplication, proofreading, and logical thinking. These intervention studies are less subject to error by confounding from other factors than cross sectional studies. All five intervention studies reported statistically significant increases in some aspects of performance with increased ventilation rate, but sometimes the performance increases were significant for only a minority of measures of performance. Overall, this body of research provides compelling evidence of an association of improved student performance with increased classroom ventilation rates.

Table 2 also includes 11 studies of the associations of school ventilation rates or CO_2 concentrations with either health symptoms determined via questionnaires or measured signs of health such as nasal patency which indicates openness of the nose or indicators of inflammation in nasal passages. Most of these studies have focused on measures of respiratory health such as nasal symptoms, allergy symptoms, or nasal openness. Only two of 11 studies are intervention studies[43, 44] less subject to error by confounding. Of the nine cross-sectional studies, six employed multivariate models to control for potential confounding. Eight out of 11 studies report statistically significant improvements in at least some health symptom or sign of health with increased ventilation rates[17, 18, 22, 23, 29, 34, 36, 45], although all studies also found some health symptoms or signs of health to not be associated with ventilation rate. Two studies included measures of nasal patency which indicates nasal openness[29, 34] and both found improvements with increased ventilation. One study measured markers in inflammation in the nose[46] and found decreased inflammation with increased ventilation. Among the two intervention studies, one reported essentially no significant effects of ventilation rates on symptoms[44] and one reported no significant effects for all symptoms except eye symptoms which increased slightly at higher ventilation rates[43]. Overall, given that eight of 11 studies report statistically significant improvements in health outcomes, this research suggests improvements in measures of respiratory health with increased ventilation rates, but the evidence of improvement in health is not as compelling as the evidence of improvements in student performance.

Five of the studies in Table 2 investigated the association of ventilation rates or CO_2 concentrations with total absence or illness absence. None are intervention studies. Four out of five studies[13, 19, 20, 28] found statistically significant decreases in absence rates with more ventilation or lower CO_2 concentrations. All of these studies used multivariate analysis models to control for potential confounders. The strongest study, which followed 162 classrooms for two years[20], found a 1.6% decrease in absence for each 1 L/s (2 cfm) per person increase in ventilation rate. The study results indicate a potential to reduce absence by several percent since it was feasible to increase ventilation rates in most classrooms by at least a few L/s (several cfm) per person. Another study found absence decreasing by 0.4 days per year for each 100 ppm decrease in CO_2 concentration[13]. Since it is practical to reduce classroom CO_2 by at least a few 100 ppm in many classrooms, the study results suggests a potential to decrease absence by a couple of days per year. Overall, the available research indicates that increased ventilation rates in classrooms are associated with reduced student absence, but the available data are limited. For both elementary and middle school students, reduced student absence has been shown to be associated with higher grade point averages and higher scores in academic achievement tests[47].

Table 2. Summary of studies of associations of health, performance or absence with ventilation rates or carbon dioxide concentrations in schools.

Study Features	Key Ventilation Rate-Related Findings	Reference
This intervention study compared cognitive performance of approximately 215 students in 12 classrooms from 6 primary schools in England, with and without outdoor air supply by a mechanical ventilation system. The study attempted to maintain temperatures the same with low and high ventilation rates but temperature control was not fully successful and the analysis of the effects of ventilation did not control for differences in temperature.	With mechanical outdoor air ventilation, ventilation rates were increased from approximately 1 to 8 L/s (2.2 to 17.0 cfm) per student. Cognitive performance, a combination of speed and accuracy, increased by 2.2% to 15% in fours tests of cognitive performance. There were no statistically significant changes in performance in five additional tests of cognitive performance. Note that data from two additional schools in which there was little change in ventilation rate were not included in the analysis	[40]
In a single naturally ventilated primary school classroom in England with an air conditioner that provided no outdoor air, cognitive performance of 18 students was measured during reference periods and during intervention periods with window opened.	CO_2 levels were 2909 ± 274 ppm without window opening and 690 ± 122 ppm with window opening. Temperatures ranged from 22.7 to 23.6 without window opening and from 22.4 to 24.4, with one outlier of 22.8 with window opening. The “power of attention” which indicates intensity of concentration improved 5% with windows opened. There were no statistically significant effects of window opening on accuracy or picture recognition.	[41]
This cross sectional study measured environmental conditions in nine naturally ventilated schools in Greece and used questionnaires to assess students’ health symptoms and perceptions of the indoor environment.	There was a statistically significant increase in allergy symptoms but not headache, throat irritation, or cough with higher CO_2 concentrations, but the analysis did not control for potential confounding by other factors	[45]
This cross sectional study of 1019 students in 51 elementary schools in Portugal measured some indoor air quality parameters and used questionnaires to assess students’ health symptoms. The classroom ventilation types were not described.	This study found lack of concentration associated with higher CO_2 concentration, but there were no statistically significant associations of CO_2 levels with health effects. It appears that the analysis did not control for potential confounding by other factors.	[11]

Table 2. continued

Study Features	Key Ventilation Rate-Related Findings	Refer-ence
This cross sectional study measured carbon dioxide concentrations in 60 naturally-ventilated primary school classrooms in Scotland, and assessed the association of carbon dioxide levels with student attendance and educational attainment.	For each 100 ppm increase in time average, but not peak, CO_2 concentration student attendance decreased by about 0.4 days per year, controlling for socio-economic status and class size. Classroom temperature and relative humidity did not affect attendance. There were no statistically significant associations of CO_2 concentrations with academic performance as measured on standard tests, after controlling for attendance.	[13]
This cross sectional study evaluated associations of ventilation rates with student academic achievement in 100 fifth-grade mechanically-ventilated classrooms from 100 US schools. Academic achievement was based on scores on standardized tests The analysis model controlled for potential confounding by socioeconomic factors	Considering the 87 classrooms with ventilation rates less than recommended in a minimum ventilation standard, there was a 2.9% (0.9% to 4.8%) increase in students passing the math test and a 2.7% (0.5% to 4.9%) increase in students passing the reading test.	[16]
This cross sectional study evaluated associations of ventilation rates with student academic achievement in 140 fifth-grade mechanically-ventilated classrooms from 100 US schools. Academic achievement was based on scores on standardized tests The analysis model controlled for potential confounding by socioeconomic factors, days of absence, highest degree held by the teacher, and classroom temperature.	Scores on the mathematics test increased by 5% for each 1 L/s (2.2 cfm) per person increase in ventilation rate. There were similar, but non-statistically significant, associations of ventilation rates with scores in the reading and sciences tests. Higher ventilation rates were associated with a decrease in visits to the school nurse for respiratory symptoms but not with statistically significant change in visits for gastro-intestinal symptoms. Ventilation rates were not significantly associated with student absence.	[38] [17]
In a cross sectional study in nine elementary schools in Austria, cognitive performance of 436 students and classroom indoor air quality parameters were measured and determined via inspections. Analysis of the association of CO_2 concentration with cognitive performance controlled for potential confounding by personal factors including parental education. The classroom ventilation methods were not described.	Reduced student cognitive performance was associated with higher classroom CO_2 concentrations.	[42]
This cross sectional study of 2453 fourth-grade students in 12 naturally-ventilated schools in Korea measured indoor air quality parameters in classrooms and used a questionnaire to obtain data on respiratory symptoms and home characteristics. The analysis control for potential confounding by personal and home environmental factors.	There was a small but statistically significant increase in wheeze with increased classroom CO_2 [odds ratio 1.03 (1.001 – 1.06) per 100 ppm increase]. There were no significant associations of CO_2 levels with doctor-diagnosed asthma or current asthma.	[18]
This cross sectional study of 12 mechanically ventilated US schools, measured CO_2 concentrations, collected data on school mechanical systems, and used a questionnaire to assess health symptoms of 403 staff.	There were no statistically significant associations of CO_2 concentrations with health complaints of staff. The analysis did not appear to control for any potential sources of confounding.	[48]
Data on sick leave over an 11 week period were collected for 635 children attending 20 day care centers in Denmark. 18 centers had balanced mechanical ventilation and 2 centers had natural ventilation. Ventilation rates were determined from rates of decay of CO_2 concentrations and CO_2 concentrations during occupancy were measured. Ventilation rates were also determined with a perfluorocarbon tracer gas, but these rates reflect ventilation during periods both with and without occupancy. Some analyses controlled for gender and age, sleeping outside, and municipality, temperature, and humidity.	CO_2 concentrations were generally low, with a median of 579 ppm during occupancy. A higher ventilation rate based on the decay of CO_2 concentration was associated with a decrease in sick days (12% decrease per 1 h^{-1} increase in air exchange rate). There was a 2% increase in sick leave per 100 ppm increase in CO_2 during occupancy, but the association was not statistically significant. The third measure of ventilation rate, which mostly reflected periods without occupancy, was not associated with sick leave.	[19]

Table 2. continued

Study Features	Key Ventilation Rate-Related Findings	Refer-ence
CO_2 concentration, temperature, and humidity were measured continuously over two years in 162 primary school US classrooms with a mixture of mechanical and natural ventilation. Student illness absence and scores on academic achievement tests were obtained from the school district. Analyses of associations controlled for socio-economic status, age, school district, method of ventilation, air conditioning, and the prior year's test scores.	There was a statistically significant increase in sick leave with decreased ventilation rate, with ventilation rate based on CO_2 data. For each 1 L/s (2.2 cfm) per occupant increase in ventilation rate, illness absence decreased 1.6%. Test scores generally improved with increased ventilation rate, but the improvements were not statistically significant.	[20] [39]
This cross sectional study in China studied 1414 students, age 13-14, in 30 classrooms within 10 naturally ventilated schools. Selected indoor air quality parameters were measured and asthma and respiratory symptoms and demographic data were collected with a questionnaire. Associations of CO_2 with health controlled for potential confounding by personal factors, smoking, and observed water leakage and mold.	There were statistically significant increases in asthma attacks, asthma medication, and current asthma with increased classroom CO_2, with 15% to 18% increases in asthma per 100 ppm increase in CO_2. Wheeze and breathlessness were not significantly associated with CO_2 concentrations.	[22]
This cross sectional study used questionnaires to collect demographic, health symptom and classroom data from teachers in 68 teachers in 64 mechanically-ventilated classrooms in ten US schools. Classrooms were inspected and temperature, humidity, and carbon dioxide concentrations were measured. Analyses of the associations of symptoms with classroom CO_2 concentrations controlled for potential confounding by demographic and classroom factors.	Prevalence of any symptom, mucosal symptoms, and neuro-physiologic symptoms (headache, difficulty concentrating, fatigue) increased with higher peak classroom CO_2 concentration, but the association was statistically significant only for neuro-physiologic symptoms with an odds ratio of 1.3 (1.02 – 1.64) per 100 ppm increase in CO_2 concentration. Lower respiratory symptoms were not associated with CO_2 concentrations.	[23]
This intervention study in four fifth-grade naturally-ventilated classrooms from two Danish schools increased ventilation rates during some periods with an added mechanical ventilation system and employed numerical and language-based tests to measure students' performance. Students also reported health symptoms and perceptions of the indoor environment via a questionnaire. CO_2 concentration, temperature, humidity, and window opening was measured.	Increasing ventilation rates from 1.7 to 6.6 L/s per student increased number of correct answers by 3.2 % to 7.4%. Speed increased with ventilation rate and accuracy was not significantly affected. Most self-reported health symptoms and perceptions off the indoor environment were not affected by ventilation rate. There was a small increase in reported draft and eye symptoms at the higher ventilation rates.	[43]
In a cross sectional study of 50 fifth-grade mechanically-ventilated US classrooms, CO_2 concentrations were measured and scores on standard academic achievement tests were obtained from the school districts. Analyses controlled for potential confounding by male female ratio, attendance, and indicators of socio-economic status of students.	A higher score in the math test was associated with higher ventilation rates based on the measured CO_2 concentrations, but the association was only significant at the $P < 0.1$ level. There was a similar trend for the score in the reading test, but the association was not statistically significant even with the $P < 0.1$ criterion.	[27]
In a cross sectional study of 434 elementary-level US classrooms, all but two classrooms with mechanical ventilation, short term measurements of CO_2 were performed and student absence data were obtained from school districts. Analyses controlled for potential confounding by classroom-level demographic and socioeconomic factors, grade level, traditional or portable classroom, and state in which the classroom was located.	A decrease in attendance was associated with CO_2 concentrations, with a 1000 ppm increase in the difference between indoor and outdoor CO_2 concentration associated with a 10% to 20% increase in absence.	[28]

Table 2. continued

Study Features	Key Ventilation Rate-Related Findings	Reference
This five-country European cross sectional study of 654 students from 46 elementary school classrooms in 21 schools surveyed teachers about school characteristics and parents and students about respiratory health conditions, home environment, and lifestyle. Some classrooms had mechanical ventilation, others had natural ventilation. Health data were obtained from 654 students. During occupancy, a range of IAQ parameters were measured in classrooms. Clinical tests were performed on five students per classroom including acoustic rhinometry which measures openness of the nose. Analyses of associations of ventilation with health controlled for smoking at home, sex, age, and, in some instances, particle concentrations.	A classroom CO_2 concentration above, versus below, 1000 ppm was associated with statistically significant and large (approximately 100 to 200%) increases in dry cough at night and rhinitis. Using a second analysis method, the associations remained statistically significant only for dry cough at night. Per 100 ppm increase in CO_2, there were statistically significant, approximately 5%, increase in dry cough at night and wheeze. One of two measures of openness of the nose improved significantly with decreased CO_2 concentration, however, the association became non-significant when the analysis controlled for particle concentration.	[29]
In 20 mechanically third and fourth grade ventilated German classrooms, ventilation rates were varied, and 417 students completed tests of concentration performance.	Higher classroom CO_2 levels (median 2115 ppm versus median 1045 ppm) were not associated with an overall statistically significant increase in concentration performance; however, there was a statistically significant increase in errors with higher CO_2 levels.	[32]
Via questionnaire, this study collected demographic and housing data and classroom perceived indoor air quality from 1476 Swedish students in grades 1 through 7 from 39 schools. Ventilation types were not specified but at least some classrooms had mechanical ventilation. Each student completed the survey twice, the second time after two years had elapsed. Temperature, humidity, CO_2 concentrations, concentrations of other pollutants, and air exchange rates were measured in classrooms. Analyses controlled for potential confounding by age, gender, atopy, housing and school characteristics.	Higher ventilation and air exchange rates were associated with improved ratings of classroom air quality at follow-up compared to baseline and higher CO_2 concentrations were associated with degraded ratings of classroom air quality.	[33]
This study of 224 staff from 12 Swedish primary schools measured nasal patency (openness) and markers of inflammation in nasal lavage (washing) fluids. The schools had a mix of natural and mechanical ventilation. Demographic and health data, including nasal symptoms, were determined vis questionnaires. Schools were inspected, air exchange rates, temperature, and humidity were measured.	Nasal symptoms were not associated with measured air exchange rates. Lower nasal patency (reduced nasal openness) was associated lower air exchange rate after controlling for ventilation type, room temperature and other potential confounders. Increased markers of inflammation in nasal lavage fluids were associated with lower air exchange rate after controlling for ventilation type and room temperature and other potential confounders. Estimated ventilation rates per person were not associated with nasal patency or inflammation markers.	[34]
In this Danish intervention study, with and without increases in ventilation rates in two mechanically ventilated classrooms, student performance was measured and questionnaires collected data on students' health symptoms and perceptions of indoor air quality.	With the ventilation rate increased from 5.2 to 9.6 L/s (11.0 to 20.3 cfm) per person and temperatures maintained constant, students' performance on four numerical tests improved, with speed but not accuracy improved. Students' performance in tests of reading and logical thinking and students symptoms and perceptions of indoor air quality were largely unaffected by ventilation rate.	[44]
This study of 44 naturally-ventilated classrooms in ten junior high schools in China measured CO_2 concentrations, temperature, relative humidity, and concentrations of a range of pollutants. Classrooms were inspected for dampness and mold. At baseline, 2134 students provided demographic and health status data and data on health symptoms via a questionnaire. At follow up, after two years, 1325 of the students again completed the questionnaire. Analyses controlled for potential confounding by age, sex, and parental allergy or asthma	At baseline, there were no statistically significant associations of symptoms with CO_2 concentrations. In the follow up survey relative to the baseline survey, with higher CO_2 concentrations, there were 40% to 90% increases in new symptoms, and the increases were statistically significant for all but skin symptoms. Also, with higher CO_2 concentrations, there were fewer remissions of symptoms between the baseline and follow up periods, although the decreased remission of symptoms was statistically significant for only one of six symptom categories.	[36]

Influence of Ventilation Rates on Energy Use and Costs

This section reviews what has been published on the magnitude of the energy and HVAC system costs attributable to ventilation. Only three journal papers were identified that included assessments of how ventilation rates in schools affect energy use with other factors constant. The findings of these three papers are summarized along with the findings in one report[1] based on a simulation effort of a set of buildings representing the US school building stock.

Benne et al.[1] used a building energy simulation tool to model a set of school buildings intended to represent the existing US school building stock in 2003. Simulations were performed with an estimated representative mechanical ventilation rate of 6.3 L s^{-1} per person and with the mechanical ventilation eliminated. They estimated that elimination of all mechanical ventilation in the school building stock would decrease total building energy use by 4.4%. With elimination of mechanical ventilation, gas energy use for heating decreased by 16.4% and electricity use for space cooling decreased by 1.3%. With the aforementioned energy prices in January 2017, one can estimate that elimination of 6.3 L s^{-1} per person of mechanical ventilation would reduce the annual cost of gas by $0.45 per square meter and reduce the annual cost of electricity for air conditioning by $0.07 per square meter. Because occupant density was not provided, these costs cannot be estimated per occupant.

Santos and Leal[2] used a building energy simulation model to evaluate energy use with different ventilation rates for heated and air conditioned school buildings in Lisbon, Paris, and Helsinki. Several building and HVAC configurations were considered and only the base case results are reported here. They estimated that each 1 L s^{-1} per person increase in ventilation rate would increase annual energy consumption by 1.2, 1.5, and 2.0 kWh per square meter in Lisbon, Paris, and Helsinki, respectively. With their floor area of 3.2 m^2 per person and assuming energy cost $0.109 per kWh, the annual per occupant cost is $2.1, $2.7, and $3.5 for the three cities, respectively.

Becker et al.[3] performed energy simulations of prototypical heated and air conditioned classrooms in Jerusalem with and without 5 L s^{-1} per person of mechanical ventilation. The assumed occupant density was high, with 1.2 m^2 per occupant. With a north-facing window orientation, eliminating mechanical ventilation reduced annual energy consumption by 5.5 kWh m^{-2} or 20% from 27.5 to 22 kWh m^{-2}. With south facing windows, eliminating mechanical ventilation reduced annual energy use by 4.2 kWh m^{-2} or 17% from 24.5 to 20.3 kWh m^{-2}. On a per person basis, the annual energy savings were 6.7 and 5.1 kWh for north and south window orientations. With an energy price of $0.109 per kWh, the annual energy cost of 5 L^{-1} per person of mechanical ventilation is $0.73 and $0.56 per person for north and south window orientations, respectively.

Davanagere et al.[4] used a building energy simulation model to evaluate how ventilation rates would affect energy use, energy costs, HVAC system costs, and indoor humidity levels of prototypical heated and air conditioned schools in Florida's hot and humid climate. The simulations assumed ventilation rates of 2.5 and 7.5 L s^{-1} per person. The base case HVAC system had a cooling coil in the mixture of outdoor and recirculated indoor air. Increasing the ventilation rate from 2.5 to 7.5 L s^{-1} per person increased energy use by 11.7%, 10.2%, and

13.9% in Miami, Orlando, and Jacksonville, respectively, with HVAC operating costs increasing by 17.1%, 17.3%, and 19.8%. There was a 5.5% increment in first cost for an HVAC system with the capacity needed to accommodate the higher ventilation rates. For Miami it was possible to calculate an annual increase in operating cost of $4.3 per occupant and an annualized increase in HVAC first cost of $2.1 per occupant. Even with only 2.5 L s^{-1} per person of ventilation, indoor relative humidity was estimated to exceed 60% approximately 3700 h per year in Miami and Orlando and 4000 h per year in Jacksonville, with many of these hours during periods without occupants present. With the higher ventilation rates, the estimated elapsed time with a relative humidity exceeding 60% increased by 43% in Miami, 13% in Orlando, and 10% in Jacksonville.

The simulations by Davanagere et al.[4] included alternate HVAC system designs applied only when ventilation rates were increased to 7.5 L s^{-1} per person. The alternative HVAC designs were intended to better control indoor humidity levels. The simulation estimated the energy use of a HVAC system with a direct expansion cooling coil located in the outdoor air stream before this air mixed with recirculated indoor air. For Miami, relative to the base case HVAC system with 2.5 L s^{-1} per person of ventilation, this alternative HVAC system with 7.5 L s^{-1} per person of ventilation increased annual energy use by 16.3%, with annual operating costs increased by 20.3% or $7.4 per person. Initial HVAC costs were increased by 4.2% and annualized incremental first costs for the HVAC system were $1.6 per occupant. Hours during occupancy with an indoor relative humidity exceeding 60% during occupancy were reduced from 204 to approximately 20. The authors also performed simulations assuming that an enthalpy exchanger, which transfers heat and water vapor between the incoming outdoor air and exhaust airstream, was employed when the ventilation rate was 7.5 L s^{-1} per person. With this system and the increased ventilation rates, annual energy use was increased by 7.8%, with annual operating costs increased by 4.4% or $1.6 per person. Initial HVAC costs increased by 7.3% and the annualized incremental first cost for the HVAC system was $2.8 per person. Hours with an indoor relative humidity exceeding 60% during occupancy were reduced from 204 to approximately 50.

DISCUSSION

The published literature clearly indicates that ventilation rates in classrooms often fall far short of the minimum ventilation rates specified in standards. There is compelling evidence of an association of increased student performance, by a few percent to as much as 15%, with increased ventilation rates based on both cross sectional and intervention studies. There is evidence of associations of reduced respiratory health effects, such as mucosal and allergy symptoms, and of reduced student absence with increased ventilation rates. Thus, the evidence suggests that the widespread under ventilation of classrooms adversely affects student performance, attendance, and health.

It is presumed that the associations of ventilation rates with improved performance and respiratory health outcomes is a consequence of reductions in indoor air concentrations of indoor-generated air pollutants. The specific pollutants affecting performance and health are uncertain. Some, but not all, controlled exposure studies have found that increased CO_2 levels, with all other factors constant, improve cognitive performance[49-52]. Controlled exposure studies have also found that changes in ventilation rates in facilities with very low emission rates from the building envelope and furnishings, have affected cognitive performance, and have sometimes affected perceived air quality and health symptoms. In these experiments, the ventilation rates primarily affect indoor levels of carbon dioxide and other bioeffluents[52, 53].

Increasing ventilation rates in schools imposes energy costs and can increase HVAC system capital costs. Per occupant, the energy costs are small. The largest estimates are annual costs of \$2.1 to \$3.5 per person for each 1 L s^{-1} of ventilation in European cities. In Jerusalem, the estimated annual cost of 5 L s^{-1} per person of ventilation was less than \$1 per person. Depending on the HVAC design, adding 5 L s^{-1} of ventilation was estimated to increase annual energy costs by about \$2 to \$7 per person in Florida. The incremental cost of the higher capacity HVAC systems needed with higher ventilation rates were only estimated for schools in Florida, and on a per-person basis these costs were also small, about \$2 to \$3 per person per year. In less hot and humid climates, smaller incremental capital costs would be expected.

The economic value of increases in student performance and health and of reductions in absence are not easily quantified. However, the annual incremental energy and capital costs of increasing ventilation rates as needed to meet or exceed current standards, range from a few dollars to about ten dollars per person. For reference, these costs can be compared to the US per student annual spending of \$10.3K in 2009 for public elementary and secondary schools[54]. Thus, the energy and capital costs of increasing ventilation rates would be less than 0.1% of education spending. Such expenditures seem like a small price to pay given the evidence of health and performance benefits.

There is little published information on the measures necessary to reduce the widespread under ventilation of classrooms. Many of the studies of CO_2 concentrations are from naturally ventilated schools and it is clear from the data that schools cannot consistently rely on opening of windows sufficiently to provide the recommended minimum ventilation rates. Sensors that provide a visual warning signal when CO_2 concentrations are elevated helped to prompt windows use in a study by Wargocki and Da Silva[55].

Low ventilation rates, relative to the minimum ventilation requirements specified in standards, and associated high CO_2 concentrations relative to 1000 ppm, are also found in many mechanically ventilated schools. For example, all 51 classrooms in one school district in the study of Mendell et al.[20] were mechanically ventilated and, based on more than 8,000 days of monitoring, median and mean ventilation rates were only 2.6 and 3.1 L s^{-1} per occupant. Also, in a study of 100 fifth-grade mechanically ventilated classrooms in the U.S. southwest, the average CO_2 concentration was 1780 ppm with a standard deviation of 850 ppm and a peak of 6000 ppm[16]. We lack systematic data on the reasons for low ventilation rates in mechanically ventilated schools. Anecdotally suggested reasons include:

- many ventilation systems are operated, potentially to save energy, such that ventilation is provided only when there is a need for heating and cooling;
- ventilation systems are turned off because they are noisy and the noise is bothersome and interferes with learning;

- ventilation systems are poorly designed or poorly maintained; and
- to reduce energy costs, ventilation is intentionally limited in some schools by closing outdoor air intake dampers.

These explanations suggest that mechanical ventilation control systems should be designed and operated to provide sufficient ventilation even when the need for heating and cooling is minimal and that mechanical ventilation systems should not be noisy. Better communication of the low energy costs and increased health and performance benefits of classroom ventilation might motivate actions to avoid low classroom ventilation rates. Also, deployment of sensors that provide a visual warning signal when CO_2 concentrations are elevated, found to be helpful in naturally ventilated classrooms, might also help stimulate corrective actions in mechanically ventilated classrooms.

To the best of the author's knowledge, this paper represents the first comprehensive review of ventilation rates and CO_2 concentrations in schools, their associations with health and performance of occupants, and their effects on energy consumption. Strengths include the assessment of these three issues in a single review, the extensive search for literature, and the reliance on papers published in refereed archival journals. As with all reviews, this one has limitations. The review relied on many cross-sectional studies that can identify associations of ventilation rates with health and performance outcomes but that cannot prove causation. Publication bias, in which a higher proportion of studies with positive findings are published, cannot be ruled out. The diversity of studies was too high for a formal statistical meta-analysis of the associations of ventilation rates with occupant health and performance outcomes. Consequently, conclusions were necessarily based on judgments reflecting consistency of findings, numbers of studies with consistent findings, and indicators of study quality such as study size and extent of control for potential confounders.

CONCLUSIONS

Ventilation rates in classrooms often fall far short of the minimum ventilation rates specified in standards. The evidence of an association of increased student performance with increased ventilation rates is compelling. There is evidence of associations of reduced respiratory health effects and reduced student absence with increased ventilation rates. Increasing ventilation rates in schools imposes energy costs and can increase HVAC system capital costs. The net annual costs, ranging from a few dollars to about ten dollars per person, are less than 0.1% typical public spending on elementary and secondary education in the US. Such costs seem like a small price to pay given the evidence of health and performance benefits.

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