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TESTIMONY TO MAINE STATE LEGISLATURE ON VENTILATION AIR FOR PUBLIC SCHOOLS-LD 705

My name is Bruce Colburn, and I am a registered professional engineer in the State of Maine. I have a Ph.D. in Engineering and serve as a consultant to numerous Maine School Districts. I am in favor of LD 705. I come here today to speak on the topic of ventilation air for schools and the problems I see specifically in Maine schools. There is a serious shortage of properly conditioned outside air that is not getting admitted into classrooms at many schools in Maine. This finding comes from installing extensive instrumentation in many Maine based school facilities. This allows long term data tracking that I couple with my personal observations to bring you first hand knowledge of the HVAC systems installed in the schools today. This should be of concern to you as the lack of fresh outside air in Maine schools has a detrimental impact on learning ability of young students. *But the situation is solvable.*

Due to the COVID problem in particular, I have been testing, analyzing and helping redesign heating and ventilation systems for schools in Maine. I have found significant deficiencies in the amount of fresh air in classrooms as demonstrated by actual logged CO2 levels. CO2 is utilized as a "surrogate" for lack of fresh air. Levels of CO2 beyond 700 ppm (parts per million) above the background "ambient" is detrimental to health and learning. Typical background levels of ambient CO2 outdoors in Maine are about 400-450 ppm, meaning that total CO2 readings above a maximum level of 1100 ppm, as measured in classrooms, are detrimental to learning.

I have measured CO2 levels in numerous Maine schools far exceeding the recommended maximum level of 1100 ppm of CO2, to a level of even as high as 2500 ppm, which is in a word, *terrible*. What has been shown by scores of researchers here in the US and abroad is that student cognitive learning is severely impaired by excessive CO2 levels. This is directly linked to inadequate ventilation levels. Research shows that testing scores are definitely lower, and in general students are lethargic, due to what we think of as a "stuffy room". We often find mechanical ventilation system failures, or the existing mechanical systems old age and dilapidated condition cannot deliver sufficient outside air, even though the building codes mandate it.

I have found that Maine schools tend to keep ventilation equipment in place too long, allowing serious degradation to occur. This saves capital expenditure, but at the expense of student learning. The COVID situation has further highlighted this deficiency as it has been more important than ever to provide proper ventilation air to "cleanse" the learning spaces we call classrooms.

Too many of such air systems in public schools are not capable of doing their job, and are in need of desperate replacement, now. Funding is needed to aid the schools in this quest. The funding would support a professionally designed, properly installed and fully commissioned ventilation system to give students the opportunity they deserve to learn in a "healthy building" versus being saddled with sick building syndrome.

I attach for your information a number of studies that have been done which document the impact of elevated CO2 levels versus various learning abilities. The data shows dramatically that as the total ppm of CO2 gets above 1100ppm there is a sharp drop in learning ability, and this directly correlates with the need for better outdoor air mechanical systems in schools. The children of this state deserve to have a better learning environment and districts need financial support from the private sector or the State of Maine for this to be implemented.

Sincerely,

Bruce K. Colburn

Bruce K. Colburn, Ph.D., P.E., CEM
Principal
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Attachments:

Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments

Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments

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Background: The indoor built environment plays a critical role in our overall well-being because of both the amount of time we spend indoors (~90%) and the ability of buildings to positively or negatively influence our health. The advent of sustainable design or green building strategies reinvigorated questions regarding the specific factors in buildings that lead to optimized conditions for health and productivity.

Objective: We simulated indoor environmental quality (IEQ) conditions in "Green" and "Conventional" buildings and evaluated the impacts on an objective measure of human performance: higher-order cognitive function.

Methods: Twenty-four participants spent 6 full work days (0900–1700 hours) in an environmentally controlled office space, blinded to test conditions. On different days, they were exposed to IEQ conditions representative of Conventional [high concentrations of volatile organic compounds (VOCs)] and Green (low concentrations of VOCs) office buildings in the United States. Additional conditions simulated a Green building with a high outdoor air ventilation rate (labeled Green+) and artificially elevated carbon dioxide (CO_2) levels independent of ventilation.

Results: On average, cognitive scores were 61% higher on the Green building day and 101% higher on the two Green+ building days than on the Conventional building day ($p < 0.0001$). VOCs and CO_2 were independently associated with cognitive scores.

Conclusions: Cognitive function scores were significantly better under Green+ building conditions than in the Conventional building conditions for all nine functional domains. These findings have wide-ranging implications because this study was designed to reflect conditions that are commonly encountered every day in many indoor environments.

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Introduction

The increasing cost of energy in the 1970s led to a change in building practices throughout the United States as buildings were increasingly constructed to be airtight and energy efficient. These changes are reflected in decreasing air exchange rates in homes and office buildings. For homes, beginning in this time period, typical air exchange rates began decreasing from approximately 1 air change per hour (ACH) to approximately 0.5 ACH [Chan et al. 2003; Hodgson et al. 2000; American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) 2013b].

Homes built since 2000 are designed to be even more energy efficient and therefore can be even tighter [0.1–0.2 ACH (Allen et al. 2012; ASHRAE 2013b)]. The > 100-year story of ventilation in buildings is complicated and was neatly summarized recently by Persily (2015). Persily describes the original ASHRAE 62 standard, issued in 1973, and the many subsequent iterations (e.g., ASHRAE 62.1 applies to commercial buildings), demonstrating the evolving nature of our understanding regarding the relationship between ventilation rate and acceptable indoor air quality. Similarly to the history of home ventilation, commercial ventilation requirements were lowered in the early 1980s, largely as an energy-conservation measure (Persily 2015).

With such design changes comes the potential for negative consequences to indoor environmental quality (IEQ) because decreased ventilation can lead to increased concentration of indoor pollutants. Building-related illnesses and sick building syndrome (SBS) were first reported in the 1980s as ventilation rates decreased (Riesenberg and Arehart-Treichel 1986), with significant annual costs and productivity losses due to health symptoms attributable to the indoor environment (Fisk and Rosenfeld 1997). A few factors of the indoor and work environments have been found to be associated with occupant health. These factors include environmental measures, such as humidity; building factors, such as ventilation rate; workspace factors, such as the presence of chemical-emitting materials; and personal factors, such as job stress, allergies, and sex (Mendell 1993; Wargocki et al. 2000; Bornehag et al. 2005; Hedge 2009; Hedge and Gaygen 2010; Nishihara et al. 2014).

The IEQ problems that arose from conventional buildings with a tight envelope contributed to the advent of sustainable design or "green" building rating systems [e.g., U.S. Green Building Council's (USGBC's) Leadership in Energy and Environmental Design (LEED®)]. These rating systems aim to reduce the environmental footprint of buildings and to improve occupant health by providing design credits to new and existing buildings for adopting green design, operation, and maintenance. Different levels of ratings for the building are then awarded based on the number of acquired credits (e.g., silver, gold, platinum) (USGBC 2014). Many design credits are aimed at energy efficiency and environmental performance but also include guidelines for improving ventilation and filtration, using low-emitting materials, controlling indoor chemical and pollutant sources, improving thermal and lighting conditions, and offering daylight views to building occupants (USGBC 2014). Compared with conventional buildings, environmental measurements in green buildings show lower concentrations of several key pollutants including particles, nitrogen dioxide, volatile

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organic compounds (VOCs), and allergens (Colton et al. 2014; Jacobs et al. 2015; Noris et al. 2013). However, these reductions generally did not extend to carbon dioxide (CO_2) or air exchange rate, demonstrating the influence of energy efficiency on green building operation and design. Green buildings were associated with improved IEQ and have been associated with reductions in self-reported symptoms in people inhabiting the buildings and with improved productivity in home, school, and office settings (Colton et al. 2014; NRC 2007; Singh et al. 2010). However, an important limitation of these studies is their reliance on subjective outcome measures, such as surveys, that have the potential for bias because participants are aware of their status (i.e., green or control). To date, we know of no studies that have been conducted in green buildings where participants were blinded to their building condition (Allen et al. 2015).

We designed this study to objectively quantify the impact of indoor environment on higher-order cognitive function, a driver of real-world productivity in office workers. We simulated low-VOC ("Green") and high-VOC ("Conventional") building conditions, both at the ASHRAE standard ventilation rate. Recognizing that technological advances in mechanical systems open the possibility of increasing ventilation rates without sacrificing energy efficiency, we also tested another building condition that introduced higher rates of ventilation to the Green building condition. This condition was labeled Green+. Last, we were motivated by the recent findings by Satish et al. (2012) that CO_2 may be a direct pollutant and not just an indicator of ventilation; therefore, we assessed cognitive function after a full-workday exposure to CO_2 while holding other variables constant.

Methods

Study Design

This study was undertaken in a controlled office environment to estimate the effects of several indoor environmental quality parameters on an objective measure of cognitive function. We used a double-blinded study design that included repeated measures of cognitive function on the same individual, characterization of potential confounding IEQ variables, and midweek testing to avoid Monday/Friday effects. All participants received the same exposures on each day, with exposures varying each day.

Study Population

Twenty-four professional-grade employees (architects, designers, programmers, engineers, creative marketing professionals, managers) in the Syracuse, New York, area participated in a 6-day longitudinal study of cognitive performance and building conditions (Table 1). Six additional people were originally recruited as backups but were not enrolled in the study. Participants were recruited through emails to local businesses. The study population was restricted to nonsensitive persons by excluding current smokers and people with asthma (because of testing indoor-air quality), claustrophobia, and schizophrenia (because this was an experiment where participants were required to remain in the laboratory). The participants were relocated to the Willis H. Carrier Total Indoor Environmental Quality (TIEQ) Laboratory at the Syracuse Center of Excellence (CoE) for 6 days over the course of 2 weeks in November of 2014. The study protocol was reviewed and approved by the Harvard T.H. Chan School of Public Health Institutional Review Board (IRB). SUNY Upstate Medical and Syracuse University ceded their review to Harvard's IRB. All participants signed informed consent documents and were compensated with $800.

Participants reported to the CoE on Tuesday, Wednesday, and Thursday, at 0900 hours, for 2 consecutive weeks. The CoE has two nearly identical office environments located adjacent to one another as part of the TIEQ Lab, each with 12 cubicles. The rooms are similarly constructed and have identical building materials (e.g., carpeting, cubicles, painting, computers). Environmental conditions, described in the following sections, were designed to be consistent in the two rooms. On the first day, the participants were randomly assigned to cubicles in the TIEQ Lab for the duration of the study. Participants were requested to spend the entire work day in the simulated office environments performing their normal work activities. They were provided with computers, internet access, and an area for private telephone calls and printing. A 45-min lunch break was given between 1200 and 1245 hours (Room 1) or 1215 and 1300 hours (Room 2). A limited selection of food was provided, served, and eaten in a room adjacent to the two simulated office environment rooms. Participants then returned to the simulated office environment to continue their work. Cognitive testing was initiated at 1500 hours each day, after which the participants completed the daily surveys and left the TIEQ Lab. Participants were blinded to test conditions, as were the analysts performing the cognitive function assessment. Participants were not given any instructions regarding how to spend their time in the evenings or on the Mondays before starting the test period.

Indoor Environment Simulation

The different environmental simulations in the TIEQ Lab on each day were designed to evaluate commonly encountered conditions and guidance values (Table 2). The three test parameters that were experimentally controlled were ventilation with outdoor air, CO_2, and VOCs. We selected two outdoor air ventilation rates for this study: 20 cfm/person and 40 cfm/person. LEED® specifies that mechanically ventilated spaces must meet ventilation rates under ASHRAE 62.1 or the local equivalent, whichever is more stringent (USGBC 2014; ASHRAE 2013a). Many local building codes use the previous ASHRAE standard of 20 cfm/person, which corresponds to an indoor CO_2 concentration of 945 ppm. Therefore, 20 cfm/person was the ventilation rate we used for the Green and Conventional simulation days because it reflects the minimum required ventilation rate for both green buildings (through LEED®) and conventional buildings (through ASHRAE). We also sought to evaluate the impact of a doubling of that minimum rate to 40 cfm/person (labeled Green+ days), which corresponds to an approximate steady-state CO_2 concentration of 550 ppm. To ensure blinding, air movement was maintained at 40 cfm per person on all study days, with 100% outdoor air ventilation used on Green+ days and moderate and high CO_2 days, and a mix of 50% outdoor air and 50% recirculated air used on the Green and Conventional days to achieve 20 cfm outdoor air ventilation per person.

For the assessment of the independent association of CO_2 concentration with cognitive function, the outdoor air ventilation rate was held constant at 40 cfm/person while CO_2 was added to the chambers to reach three steady-state CO_2 concentrations. The first target was 550 ppm (Green+, Days 1 and 6). The second target, 945 ppm, was selected

Table 1. Participant demographics.

Category	n	%
Sex		
Male	10	42
Female	14	58
Age		
20–30	8	33
31–40	3	12
41–50	6	25
51–60	4	17
61–70	3	12
Ethnicity		
White/Caucasian	22	92
Black or African American	1	4
Latino	1	4
Highest level of schooling		
High school graduate	1	4
Some college	2	8
College degree	13	54
Graduate degree	8	33
Job category		
Managerial	5	21
Professional	15	63
Technical	1	4
Secretarial or clerical	1	4
Other	2	8

to reflect a level that would be expected at the previously described ASHRAE minimum recommended ventilation rate of 20 cfm outdoor air/person. The third target, 1,400 ppm, was selected to represent a higher, but not uncommon, concentration of CO_2 found in indoor environments [1,400 ppm is the maximum observed 8-hr time-weighted-average CO_2 concentration in the U.S. Environmental Protection Agency (EPA) BASE data set (U.S. EPA 1998)]. On Days 2 and 3, when the independent effects of CO_2 were tested, CO_2 was added from a cylinder of ultra-pure CO_2 (≥ 99.9999% pure) to the TIEQ Lab supply air at a rate needed to maintain steady-state CO_2 concentrations of 945 ppm and 1,400 ppm. Because CO_2 concentrations are affected by occupancy and mixing impact concentrations, a technician monitored CO_2 in real time and adjusted the emission rate accordingly to maintain constant CO_2 concentrations. During Days 4 and 5 (Green and Conventional), injection of pure CO_2 was not needed to reach the target CO_2 concentrations because of the reduced outdoor ventilation rate. A protocol was established to ensure participant safety in the event that there were unexpected deviations. CO_2 was monitored in real time at a high spatial resolution in the test rooms using three different and independently calibrated monitors. A technician seated next to the CO_2 shut-off valves monitored the CO_2 concentrations during the entire test period. The protocol called for immediately canceling the testing if CO_2 concentrations exceeded preset thresholds that were well below occupational health limits [2,500 ppm, one-half of the threshold limit value set by the American Conference of Governmental Industrial Hygienists (ACGIH 2015)]. No deviations from protocol occurred during the study.

The TIEQ Lab was constructed with low-VOC materials, and low levels of VOCs were confirmed by pretesting (Table 3). To simulate a conventional office space with elevated VOCs, we placed VOC sources in the diffuser that supplied air to each cubicle area before the participants arrived on Day 5. We selected a target total VOC (TVOC) level of 500 μg/m^3 based on the LEED® Indoor Air Quality Assessment credit limit, as measured using U.S. EPA method TO-15 (USGBC 2014). The diffusers were built into the floor of the TIEQ Lab, and there were no visible indicators of these sources for the participants to observe. We selected a mix of nonodoriferous sources to simulate VOC-emitting materials that are commonly found in office buildings and that covered four indoor VOC source categories including building materials [56 in^2 (360 cm^2) exposed edge melamine, 56 in^2 (360 cm^2) exposed edge particle board, 64 in^2 (415 cm^2) vinyl mat], adhesives [80 in^2 (520 cm^2) duct tape, 80 in^2 (520 cm^2) packing tape (exposed)], cleaning products [1 oz. (30 mL) multi-surface cleaner, 4 multi-surface wipes, 144 in^2 (930 cm^2) recently dry-cleaned cloth], and office supplies (4 dry erase markers, 1 open bottle of correction fluid).

Environmental Monitoring

The study team characterized the TIEQ Lab on each test day for a wide range of IEQ indicators: CO_2, temperature, relative humidity, barometric pressure, sound levels, VOCs, aldehydes, nitrogen dioxide (NO_2), ozone (O_3), particulate matter ≤ 2.5 μm in diameter ($PM_{2.5}$), and light. Netatmo Weather Stations were installed in each cubicle to measure temperature, humidity, carbon dioxide concentrations (parts per million), and sound levels (decibels) every 5 min for each participant. The stations were calibrated to 0 and 3,000 ppm CO_2 using calibration gases and were validated using a calibrated TSI Q-Trak (model 7575). In addition, the Netatmos were tested with 400 and 1,000 ppm calibration gas at the end of the study to determine if the sensors drifted during the 2-week period. Duplicate measures of CO_2 were collected in each room using a TSI Q-Trak model 7575 and two K-33 data loggers. Summa canisters were used to detect overall levels of 62 common VOCs in a randomly selected workstation in each room for each of the study days (Table 3). An additional sample was collected in a third randomly selected cubicle each day. Samples were analyzed by ALS Laboratories according to U.S. EPA method TO-15 (U.S. EPA 1999). Thirty-six VOCs were not detected in any of the samples.

In each room, a monitoring station was placed at the far end of the room from the entrance to monitor additional IEQ parameters. The station included *a*) a TSI SidePak AM510 personal aerosol monitor to measure $PM_{2.5}$, *b*) an integrated filter sample for gravimetric analysis of $PM_{2.5}$ and elemental composition, *c*) an 8-hr integrated active air sample (0.4 L/min flow rate) analyzed for 14 aldehydes by ALS Analytical Laboratories using U.S. EPA method TO-11 (U.S. EPA 1999), *d*) a passive NO_2 badge [8-hr time-weighted average; model X-595, Assay Technology; Occupational Safety and Health Administration (OSHA) method 182 (OSHA 1991)], *e*) a passive sampling badge for O_3 [8-hr time-weighted average; model X-586, Assay Technology; OSHA Method 214 (OSHA 2008)], and *f*) illuminance and irradiance measures using an IL1400 radiometer/powermeter with SEL-033/Y/W and SEL-033/F/W detectors. VOC, aldehyde, NO_2, O_3, and integrated $PM_{2.5}$ samples had at least one blank and one duplicate for every

Table 2. Average indoor environmental conditions simulated in each room of the TIEQ lab.

Variable	Day 1 Green+		Day 2 Moderate CO_2		Day 3 High CO_2		Day 4 Green		Day 5 Conventional		Day 6 Green+	
Date	4 November		5 November		6 November		11 November		12 November		13 November	
Day of the week	Tuesday		Wednesday		Thursday		Tuesday		Wednesday		Thursday	
Room	502	503	502	503	502	503	502	503	502	503	502	503
Experimental parameters												
CO_2 (ppm)	563	609	906	962	1,400	1,420	761[b]	726[b]	969	921	486	488
Outdoor air ventilation (cfm/person)[a]	40	40	40	40	40	40	20	20	20	20	40	40
TVOCs (μg/m^3)	43.4	38.5	38.2	28.6	32.2	29.8	48.5	43.5	506	666	55.8	14.9
Other environmental parameters												
Temperature (°C)	23.9	24.5	22.4	23.9	21.3	22.0	22.9	23.7	21.8	22.5	20.7	21.3
Relative humidity (%)	31.0	30.4	34.2	31.6	38.7	38.3	34.3	33.3	39.6	38.3	27.8	26.8
NO_2 (μg/m^3)	57.9	58.9	53.2	54.1	60.8	58.4	51.3	45.6	54.6	50.8	56.5	55.5
O_3 (μg/m^3)	3.42	21.2	14.4	13.0	1.37	0.00	6.85	238	1.71	1.37	4.11	6.85
$PM_{2.5}$ (μg/m^3)	2.38	3.49	3.35	2.58	2.97	2.42	1.26	1.83	1.68	1.34	1.26	1.38
Noise (dB)	51.3	49.9	49.7	48.8	52.5	48.8	49.6	48.7	51.1	48.8	50.5	49.2
Illuminance (mV)	2.95	2.70	2.89	2.83	2.31	2.04	3.11	2.93	2.74	2.51	2.39	2.28
Irradiance (mV)	9.07	8.76	9.45	9.37	6.00	6.05	9.90	9.60	8.30	8.14	6.70	6.82

Abbreviations: TIEQ, Total Indoor Environmental Quality; TVOCs, total volatile organic compounds.
[a]A constant air flow rate of 40 cfm/person was maintained on all study days, with 100% outdoor air used on days 1, 2, 3, and 6 and 50% outdoor air and 50% recirculated air used to achieve an outdoor air ventilation rate of 20 cfm/person on days 4 and 5. [b]Average concentration from 1400 to 1700 hours was 926 ppm, but lower CO_2 concentrations in the morning hours during the approach to steady state led to a lower average CO_2 concentration.

10 samples. Samples were blank-corrected for analyses. All duplicate measures were within 15% of each other, and an average of the two was used for subsequent analyses.

An ambient air monitoring system was installed on the roof of the CoE to measure $PM_{2.5}$, O_3, and NO_2 using the same procedures and equipment as the indoor stations to establish the potential influence of outdoor contaminants on the indoor environment. Outdoor temperature, humidity, solar radiation, and wind speed/direction data were obtained from the CoE weather station located on the roof of the building. Baseline (i.e., before occupancy) measurements of all IEQ parameters were collected in the TIEQ Lab 1 month before the study was performed.

Cognitive Function Assessment

The cognitive assessment was performed daily using the Strategic Management Simulation (SMS) software tool, which is a validated, computer-based test that has been designed to test the effectiveness of management-level employees through assessments of higher-order decision making (Streufert et al. 1988; Breuer and Satish 2003; Satish et al. 2004). At the start of the 1.5-hr test, participants were given a brief, 1-page description of the scenario that they were about to participate in during the test. They were then logged onto a standardized desktop computer station at the TIEQ Lab using a unique identifier. Participants were not allowed to use their own computers and were instructed to turn off all other devices before the assessment. The simulation was then initiated. Participants were exposed to diverse situations based on real-world equivalent challenges (e.g., handling a township in the role of a mayor or emergency coordinator). These scenarios are designed to capture participants' standard response pattern. The software allows flexibility in approach; participants can choose to make a decision or form a plan at any time in response to any stimulus from the program. The absence of requirements or stated demands allows the participant the freedom to strategize and take initiative in his or her typical cognitive style. Based on the participant's actions, plans, responses to incoming information, and use of prior actions and outcomes, the SMS software computes scores for nine cognitive factors (Table 4).

A technician trained in administering this test was present to provide standardized instructions and periodically answer any questions from participants. Parallel scenarios (i.e., equivalent scenarios) were used from one day to the next, which allows individuals to be retested without potential bias caused by experience and learning effects (Swezey et al. 1998). Parallel scenarios have correlation coefficients between 0.68 and 0.94 for the scores on these cognitive function domains (Streufert et al. 1988).

Statistical Analyses

Generalized additive mixed effect models were used to test associations between environmental exposures and cognitive function while controlling for the correlated nature of the repeat measures. In the model, the most specific exposure was assigned to each participant, whether it be cubicle-level (CO_2), room-level

Table 3. Speciated VOC concentrations ($\mu g/m^3$) on each study day, averaged across rooms.

	Condition						
Analyte	Background	Day 1 Green+	Day 2 Med. CO_2	Day 3 High CO_2	Day 4 Green	Day 5 Conventional	Day 6 Green+
VOCs							
1,2,4-Trimethylbenzene	0.3	0.2	ND	0.1	ND	0.5	0.1
2-Butanone	2.5	0.7	0.7	0.8	1.1	1.1	0.6
2-Propanol	1.0	1.2	1.1	3.1	1.2	312.5	8.2
Acetone	12.0	14.7	9.6	8.7	20.0	20.0	8.6
Benzene	0.5	0.8	0.5	0.9	0.7	0.5	0.5
Carbon disulfide	0.6	0.2	ND	ND	ND	ND	0.1
Carbon tetrachloride	ND	0.2	0.4	ND	0.2	ND	ND
Chloroform	ND	0.1	ND	ND	ND	0.1	ND
Chloromethane	1.3	1.7	1.5	1.4	1.9	1.5	1.4
Cyclohexane	0.2	0.3	0.4	0.5	0.1	0.4	0.3
Dichlorodifluoromethane	2.5	2.6	2.9	2.7	2.9	2.4	2.5
Ethyl acetate	ND	ND	ND	ND	1.0	2.0	ND
Ethylbenzene	0.3	0.4	ND	0.3	0.2	0.1	0.1
Freon 113	0.3	0.7	0.8	0.8	0.8	0.2	0.4
Heptane	ND	0.3	ND	0.3	ND	257.5	6.9
Hexane	0.4	0.7	0.5	0.7	0.4	0.8	1.3
m,p-Xylene	0.8	1.5	0.4	1.0	1.0	0.7	0.7
Methylene chloride	0.5	0.3	0.6	0.5	0.3	0.4	0.4
o-Xylene	0.3	0.4	ND	0.4	0.1	0.3	0.1
Styrene	0.1	ND	ND	ND	ND	ND	0.1
Tetrachloroethene	3.7	0.9	ND	ND	0.9	0.6	0.2
Tetrahydrofuran	ND	ND	ND	ND	0.2	0.1	0.2
Toluene	2.4	2.1	1.4	1.9	2.2	1.9	2.9
trans-1,2-Dichloroethene	19.0	8.8	12.6	6.2	10.3	21.8	8.7
Trichloroethene	ND	ND	ND	ND	ND	ND	0.2
Trichlorofluoromethane	1.3	1.2	1.6	1.4	1.5	1.1	1.2
Grand total	50.0	40.1	35.0	31.4	46.9	626.4	45.6
Aldehydes							
2,5-Dimethylbenzaldehyde	ND	ND	ND	ND	ND	ND	ND
Acetaldehyde	1.0	3.7	3.2	3.1	5.4	7.3	2.1
Benzaldehyde	ND	ND	ND	ND	ND	1.5	ND
Crotonaldehyde	ND	ND	ND	ND	ND	ND	ND
Formaldehyde	2.4	5.9	5.5	5.4	8.9	11.7	4.4
Hexanaldehyde	ND	0.8	0.8	ND	1.9	2.4	ND
Isovaleraldehyde	ND	ND	ND	ND	ND	ND	ND
m,p-Tolualdehyde	ND	ND	ND	ND	ND	ND	ND
n-Butyraldehyde	1.1	2.7	1.4	2.3	2.8	2.4	2.0
o-Tolualdehyde	ND	ND	ND	ND	ND	ND	ND
Propionaldehyde	ND	0.7	1.2	ND	1.4	1.6	0.6
Valeraldehyde	ND	ND	ND	ND	ND	ND	ND
Glutaraldehyde	ND	0.5	ND	ND	0.4	ND	ND
o-Phthalaldehyde	ND	65.1	57.7	70.0	41.6	38.4	76.8
Grand total	4.6	79.4	69.8	80.9	62.4	65.3	85.8

Abbreviations: ND, non-detect; VOC, volatile organic compound.

Table 4. Description of the cognitive domains tested.

Cognitive function domain[a]	Description
Basic Activity Level	Overall ability to make decisions at all times
Applied Activity Level	Capacity to make decisions that are geared toward overall goals
Focused Activity Level	Capacity to pay attention to situations at hand
Task Orientation	Capacity to make specific decisions that are geared toward completion of tasks at hand
Crisis Response	Ability to plan, stay prepared, and strategize under emergency conditions
Information Seeking	Capacity to gather information as required from different available sources
Information Usage	Capacity to use both provided information and information that has been gathered toward attaining overall goals
Breadth of Approach	Capacity to make decisions along multiple dimensions and use a variety of options and opportunities to attain goals
Strategy	Complex thinking parameter that reflects the ability to use well-integrated solutions with the help of optimal use of information and planning

[a]See Streufert et al. (1986) for detailed descriptions.

(VOCs), or lab-level (ventilation). Participant ID was treated as a random intercept to control for confounding by individual characteristics. The residuals were normally distributed and homoscedastic for all models (data not shown). We used penalized splines to graphically assess linearity in the associations between environmental exposures and cognitive scores. SMS scores are often compared with normative data from other uses of the SMS software (e.g., Satish et al. 2012). Because we did not have access to normative data, we instead used our study population as the reference group. Based on the analysis, cognitive scores were normalized to Conventional (Table 5), Green (Figure 1), or Green+ (Figure 2) scores to allow for comparisons across cognitive function domains, each of which has a unique scale in its raw form. The scores were normalized for each cognitive domain by dividing all scores by the average score obtained during the normalizing condition. The statistical significance of our results was not affected by normalization. Given the multiple comparisons tested in this analysis, *p*-values < 0.001 were considered to be statistically significant after performing a Bonferroni correction. Analyses were performed using the open-source statistical package R v.3.0.0 (R Core Team 2015).

Results

Green Building and Cognitive Function

The TVOC levels were constant at < 50 μg/m^3 on all study days except the Conventional building day, when levels increased to 506–666 μg/m^3 depending on the room. The compounds that increased in concentration included but were not limited to formaldehyde, benzaldehyde, acetaldehyde, heptane, and 2-propanol. Heptane and 2-propanol had the largest increases of the sampled compounds (Table 3). Total aldehyde concentrations were primarily driven by *o*-phthalaldehyde and remained relatively constant on all study days.

Cognitive function scores were higher under the Green building condition than under the Conventional building condition for all nine functional domains (Figure 1). On average, cognitive scores were 61% higher on the Green building day and 101% higher on the two Green+ building days than on the Conventional building day. The largest effects were seen for Crisis Response, Information Usage, and Strategy, all of which are indicators of higher-level cognitive function and decision making (Streufert and Swezey 1986). For Crisis Response, scores were 97% higher during the Green condition than during the Conventional condition, and 131% higher during the Green+ condition than during the Conventional condition. For Information Usage, scores obtained under the Green and Green+ conditions were 172% and 299% higher than under the Conventional condition, respectively. Finally, for Strategy, which tested the participants' ability to plan, prioritize, and sequence actions, the Green and Green+ day scores were 183% and 288% higher than on the Conventional day, respectively (Table 5).

The raw cognitive scores for each domain were normalized to the Conventional

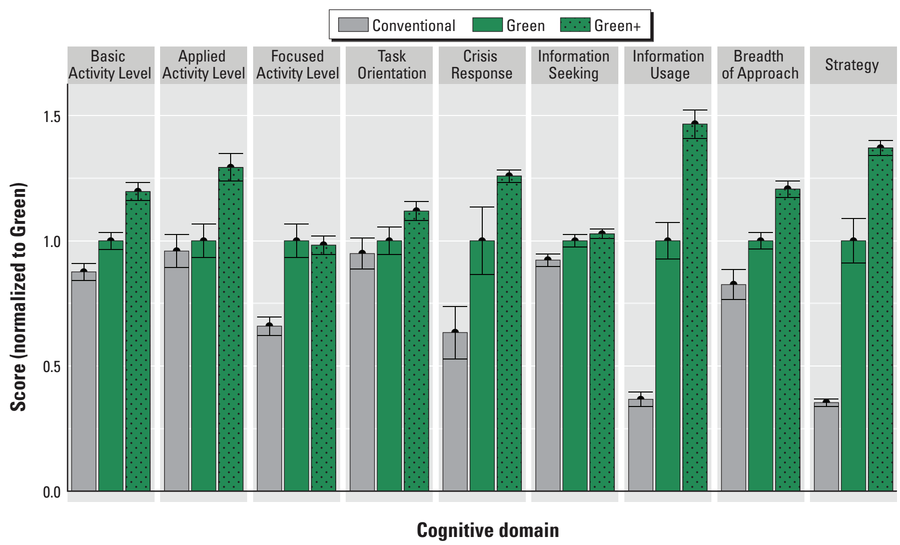

Figure 1. Average cognitive function scores and standard error bars by domain for the Conventional, Green, and two Green+ conditions, normalized to the Green condition by dividing all scores by the average score during the Green condition.

Table 5. Generalized additive mixed effect models testing the effect of IEQ condition and on cognitive scores, normalized to the "Conventional" condition, treating participant as a random intercept.

	Cognitive domain: estimate, [95% confidence interval], (*p*-value)									
Condition	Basic Activity Level	Applied Activity Level	Focused Activity Level	Task Orientation	Crisis Response	Information Seeking	Information Usage	Breadth of Approach	Strategy	Average
Day 1 Green+	1.35 [1.28, 1.43] (< 0.0001)	1.39 [1.26, 1.52] (< 0.0001)	1.44 [1.27, 1.62] (< 0.0001)	1.14 [1.11, 1.17] (< 0.0001)	2.35 [1.91, 2.78] (< 0.0001)	1.10 [1.07, 1.14] (< 0.0001)	3.94 [3.47, 4.41] (< 0.0001)	1.43 [1.25, 1.60] (< 0.0001)	3.77 [3.40, 4.14] (< 0.0001)	1.99 [1.89, 2.09] (< 0.0001)
Day 2 Moderate CO_2	1.20 [1.13, 1.27] (< 0.0001)	1.08 [0.95, 1.21] (0.23)	1.68 [1.51, 1.85] (< 0.0001)	1.05 [1.02, 1.08] (0.0009)	2.05 [1.63, 2.48] (< 0.0001)	1.11 [1.08, 1.15] (< 0.0001)	2.61 [2.15, 3.07] (< 0.0001)	1.29 [1.12, 1.46] (0.0013)	3.17 [2.81, 3.53] (< 0.0001)	1.69 [1.59, 1.79] (< 0.0001)
Day 3 High CO_2	0.91 [0.84, 0.98] (0.015)	0.88 [0.75, 1.01] (0.081)	0.85 [0.68, 1.02] (0.087)	1.00 [0.97, 1.03] (0.76)	1.33 [0.90, 1.75] (0.14)	1.08 [1.05, 1.12] (< 0.0001)	1.01 [0.55, 1.48] (0.95)	0.98 [0.81, 1.15] (0.78)	0.83 [0.47, 1.19] (0.36)	0.99 [0.89, 1.09] (0.78)
Day 4 Green	1.14 [1.06, 1.21] (0.0003)	1.04 [0.91, 1.18] (0.51)	1.51 [1.34, 1.68] (< 0.0001)	1.03 [1.00, 1.06] (0.065)	1.97 [1.54, 2.40] (< 0.0001)	1.09 [1.05, 1.12] (< 0.0001)	2.72 [2.26, 3.19] (< 0.0001)	1.21 [1.04, 1.38] (0.018)	2.83 [2.46, 3.19] (< 0.0001)	1.61 [1.51, 1.71] (< 0.0001)
Day 5 Conventional (Reference)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Day 6 Green+	1.37 [1.30, 1.44] (< 0.0001)	1.33 [1.20, 1.46] (< 0.0001)	1.52 [1.35, 1.69] (< 0.0001)	1.15 [1.12, 1.19] (< 0.0001)	2.27 [1.85, 2.69] (< 0.0001)	1.11 [1.08, 1.15] (< 0.0001)	4.04 [3.58, 4.51] (< 0.0001)	1.50 [1.33, 1.67] (< 0.0001)	3.98 [3.62, 4.34] (< 0.0001)	2.03 [1.93, 2.13] (< 0.0001)
R^2	0.34	0.17	0.33	0.03	0.28	0.06	0.69	0.27	0.79	0.81

IEQ, indoor environmental quality.

condition and modeled by study day, controlling for participant (Table 5). The repeat simulation of the Green+ day (Day 6), which was added to the study as a quality control measure, showed similar cognitive function scores: *p*-values for the null hypothesis of no difference between the 2 days ranged from 0.27 for Strategy (normalized scores of 3.77 and 3.98, respectively) to 0.73 for Crisis Response (normalized scores of 2.35 and 2.27). Under the Green+ condition, participants had statistically significantly higher cognitive function scores than under the Conventional condition in all domains ($p < 0.0001$). Under the Green condition, particpants had higher scores than under the Conventional condition in all domains, five of which were statistically significant.

Participants scored higher on the Green+ days than on the Green day in eight of nine domains, resulting in a 25% increase in scores on average when outdoor air ventilation rates were increased. Cognitive scores were 20% higher on the Green+ days than on the moderate CO_2 day when CO_2 levels were higher (*p*-value < 0.0001), and 5% higher on the moderate CO_2 day than on the Green day when outdoor air ventilation was reduced (*p*-value = 0.12). These estimates and *p*-values were produced by rerunning the "average" model in Table 5 with the Green condition as the reference category (data not shown).

The model of the average scores in Table 5 had a high R^2 value of 0.81, indicating that a significant amount of the variability in cognitive scores can be explained by these indoor-environment test conditions, leaving only 19% of the variability to be explained by all other potential intrapersonal drivers of cognitive function such as diet, the previous night's sleep quality, and mood. For the specific domains of cognitive function, the R^2 ranged from 0.03 to 0.79.

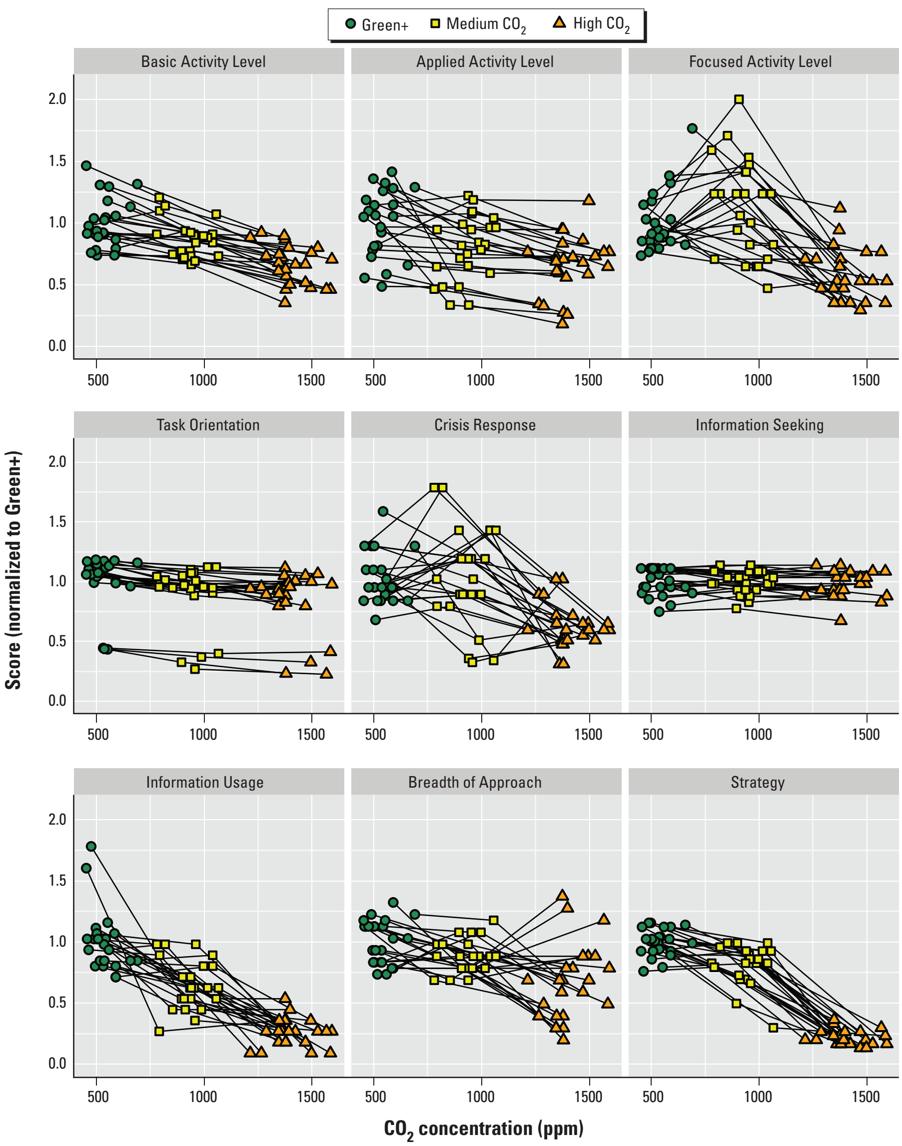

Figure 2. Cognitive function scores by domain and participant and the corresponding carbon dioxide concentration in their cubicles. Each line represents the change in an individual's CO_2 exposure and cognitive scores from one condition to the next, normalized to the average CO_2 exposure across all participants during the Green+ conditions.

Carbon Dioxide and Cognitive Function

The effects of CO_2 on cognitive function scores while all other parameters were held constant are depicted in Figure 2. Because the air in each room was not completely mixed, there was some variability in CO_2 levels between cubicles. Each line represents the change in an individual's CO_2 exposure and cognitive scores from one condition to the next, normalized to the average CO_2 exposure across all participants during the Green+ conditions. For seven of the nine cognitive function domains, average cognitive scores decreased at each higher level of CO_2 (Table 5). Cognitive function scores were 15% lower for the moderate CO_2 day (~ 945 ppm) and 50% lower on the day with CO_2 concentrations of ~1,400 ppm than on the two Green+ days (Table 5, dividing the average Green+ estimate by the moderate CO_2 and high CO_2 estimates, respectively). The exposure–response curve between CO_2 and cognitive function is approximately linear across the CO_2 concentrations used in this study; however, whether the largest difference in scores is between the Green+ conditions and the moderate CO_2 condition or the moderate CO_2 condition and the high CO_2 condition depends on the domain (Figure 2).

Ventilation rate, CO_2, and TVOCs were modeled separately from study day to capture the independent effects of each factor on cognitive function scores, averaged across all domains. A statistically significant increase in scores was associated with ventilation rate, CO_2, and TVOCs ($p < 0.0001$ for all three parameters). On average, a 400-ppm increase in CO_2 was associated with a 21% decrease in a typical participant's cognitive scores across all domains after adjusting for participant (data not shown), a 20-cfm increase in outdoor air per person was associated with an 18% increase in these scores, and a 500-μg/m^3 increase in TVOCs was associated with a 13% decrease in these scores. Although other environmental variables were not experimentally modified, some did vary over the course of the study (Table 2). There was a high degree of consistency in IEQ between the two rooms; however, ozone was significantly higher in one of the chambers on the Green day. Cognitive scores were 4% higher in the room with high ozone on this day, after accounting for baseline cognitive performance in the two rooms. These IEQ parameters were added to the model with the experimentally controlled variables and were not found to be significantly associated with cognitive function at the 0.05 significance level.

Discussion

Green Buildings and Health

We found that when participants spent a full day in a Green building, there was a significant increase in their cognitive function scores compared with when they spent a day in an environment that had been designed to simulate a conventional building by elevating VOC concentrations. The study was designed to represent conditions typically observed in many buildings; we did not include extreme exposures or choose uncommon VOC sources. Further, we selected our target levels of VOCs, ventilation rates and CO_2 to be above and below the standards in LEED®, ASHRAE, and the U.S. EPA BASE study in order to evaluate how these common standards and guidelines perform (USGBC 2014, ASHRAE 2013a, U.S. EPA 1998). Our findings indicate that there may be benefits to meeting the LEED® VOC guideline of 500 μg/m^3 and enhancing ventilation rates beyond the minimum requirement under ASHRAE.

The "Conventional" building simulation parameters in our study were based on conditions described in the U.S. EPA BASE study, which plausibly represent the upper end of performance for "typical" buildings in the United States in the 1990s because the owners were willing to participate in the study, introducing potential self-selection bias, and larger, "non-problem" buildings were preferentially recruited (Persily and Gorfain 2004). Therefore, the extent to which BASE buildings represent typical conventional buildings is unknown. Our findings show impacts above the 95th percentile of CO_2 (945 ppm) and the mean VOC concentration in the BASE study (450 μg/m^3); however, a larger proportion of the buildings in the BASE study would likely have exceeded these targets if "problem" buildings had been included in the recruitment process.

The VOC levels on the Conventional and Green/Green+ days straddled both the LEED® TVOC guidance concentration of 500 μg/m^3 and the BASE mean concentration of 450 μg/m^3. The common VOC sources that were added to the rooms during the Conventional building day led to increases in a range of VOCs. Previous testing with the SMS tool showed that 2 hr of painting, which exposed participants to VOCs, was associated with reductions in three of the five domains investigated (Satish et al. 2013). The lower TVOC concentrations (yet larger number of sources) in the present study were associated with statistically significant decrements in decision-making performance in five of the nine domains.

Carbon Dioxide and Ventilation

Carbon dioxide concentration in indoor environments has long been used as an indicator of ventilation and as a proxy for indoor air quality (ASHRAE 2013b). However, this conventional thinking is being challenged as the evidence mounts for CO_2 as a direct pollutant, not just a marker for other pollutants (Satish et al. 2012). We found statistically significant declines in cognitive function scores when CO_2 concentrations were increased to levels that are common in indoor spaces (approximately 950 ppm). In fact, this level of CO_2 is considered acceptable because it would satisfy ASHRAE's ventilation rate guidance for acceptable indoor air quality. Larger differences were seen when CO_2 was raised to 1,400 ppm.

Satish et al. used the SMS tool to test the effects of CO_2 exposures on the cognitive function of 22 participants, using a controlled chamber and injection of ultra-pure CO_2 (Satish et al. 2012). The authors reported effects on seven of nine cognitive function domains with increasing CO_2 concentration. The SMS tool was also used to test the relationship between ventilation rate and cognitive function among 16 participants (Maddalena et al. 2015). Participants scored significantly lower on eight of nine domains at low ventilation rates (12.5 cfm of outdoor air/person). In contrast to the present study, these other studies had *a*) a single experimental parameter; *b*) half-day or shorter exposures; *c*) multiple experimental conditions per day; *d*) atypical exposure targets (2,500 ppm of CO_2 and 12.5 cfm outdoor air/person); and *e*) primarily students and college-age adults. Despite these differences, our study found similar changes in cognitive scores from a unit change in CO_2 or outdoor air ventilation. Associations were consistent *a*) in all three study populations, indicating that knowledge workers and students were equally affected by CO_2 and outdoor air ventilation, and *b*) at different exposure durations, indicating that even short exposures are associated with cognitive function. Given the similarities in findings, there may not be a desensitization or compensatory response from prolonged exposure. More research is necessary to investigate the presence of these responses or the lack thereof.

The CO_2 exposure levels used in this study are comparable to those in a variety of indoor locations. Assessment of public housing units in Boston found median CO_2 levels to be 809 ppm in conventional apartments and 1,204 ppm in the newly constructed LEED® platinum apartments (Colton et al. 2014). Corsi et al. (2002) reported CO_2 concentrations > 1,000 ppm in 66% of 120 classrooms in Texas, and Shendell et al. (2004) measured CO_2 concentrations > 1,000 ppm in 45% of 435 classrooms in Washington and Idaho and reported that elevated CO_2 concentrations were associated with increases in student absences.

Strengths and Limitations

The study design has several notable strengths. These strengths include repeated measures of cognitive function on the same individual for control of between-subject variability, characterization of the TIEQ Lab for potential environmental confounders, repeated testing of the same condition 9 days apart on different days of the week, mid-week testing to avoid potential Monday/Friday bias, participants and cognitive function analysts blinded to test conditions, and the use of an objective measure of cognitive function.

The SMS tool is an objective assessment tool, unlike self-reported metrics, and thus is less susceptible to the participant's environmental perceptions. Extensive work has been dedicated to testing the validity of the SMS software; correlations between scores on these tests and other measures of productivity such as income at age and job level at age exceed 0.6 (Streufert et al. 1988). The correlations are stronger for the more strategic domains, such as strategy, information usage, and crisis response, than for domains pertaining to activity, such as information search and activity level. The domains that were most affected by the exposures in this study are the same domains that are most closely related to other measures of productivity (Streufert et al. 1988). Lastly, the concordance of the scores for the two Green+ conditions suggests that *a*) the study was internally valid, *b*) there were no learning effects associated with the test, and *c*) day of the week (Tuesday vs. Thursday) was not a potential confounding variable.

The potential for confounding or effect modification by parameters measured or otherwise was reduced by the use of the controlled environment and by repeated measures on each participant. By testing on subsequent days, it is possible that effects from one condition were reflected in the scores obtained on the next day. The environmental factors that were not experimentally modified exhibited some variability owing to changes in outdoor conditions and participant behavior. In particular, ozone levels fluctuated significantly between some IEQ conditions (Table 2). Environmental factors other than outdoor air ventilation, CO_2, and VOCs were not statistically significant predictors of cognitive scores, but the possibility of uncontrolled confounding by these factors cannot be excluded. The environmental conditions on each of the study days met design criteria. On one day (Day 4), CO_2 levels were lower in the morning than in the afternoon, which influenced the reported mean concentration. The CO_2 levels on this day were similar to the moderate CO_2 and Conventional conditions (Day 5) during the time leading up to and during the cognitive test (926 ppm from 1400 to 1700 hours). This study used a controlled environment to individually control certain contaminants. Assessments performed in actual office environments are important to confirm the findings in a noncontrolled setting.

Conclusion

Office workers had significantly improved cognitive function scores when working in Green and Green+ environments compared with scores obtained when working in a Conventional environment. Exposure to CO_2 and VOCs at levels found in conventional office buildings was associated with lower cognitive scores than those associated with levels of these compounds found in a Green building. Using low-emitting materials, which is common practice in Green buildings, reduces in-office VOC exposures. Increasing the supply of outdoor air lowers exposures to not only CO_2 and VOCs but also to other indoor contaminants. Green building design that optimizes employee productivity and energy usage will require adopting energy-efficient systems and informed operating practices to maximize benefits to human health while minimizing energy consumption. This study was designed to reflect indoor office environments in which large numbers of people work every day. These exposures should be investigated in other indoor environments, such as homes, schools, and airplanes, where decrements in cognitive function and decision making could have significant impacts on productivity, learning, and safety.

Editor's Note: *In the Information Seeking column in Table 5, the* p*-values for Day 2 (Moderate CO_2), Day 3 (High CO_2), and Day 4 (Green) have been changed to < 0.0001 from 0.61, 0.35, and 0.45, respectively. In the Information Usage column in Table 5, the* p*-value for Day 3 (High CO_2) has been changed from < 0.0001 to 0.95. The previous* p*-values were from a different reference category that was subsequently changed during the peer-review process. The new* p*-values are consistent with the current reference category, and the conclusions of the manuscript are unaffected by these changes.*

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Associations Between Classroom CO_2 Concentrations and Student Attendance in Washington and Idaho

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Abstract

Student attendance in American public schools is a critical factor in securing limited operational funding. Student and teacher attendance influence academic performance. Limited data exist on indoor air and environmental quality (IEQ) in schools, and how IEQ affects attendance, health, or performance. This study explored the association of student absence with measures of indoor minus outdoor carbon dioxide concentration (dCO_2). Absence and dCO_2 data were collected from 409 traditional and 25 portable classrooms from 22 schools located in six school districts in the states of Washington and Idaho. Study classrooms had individual heating, ventilation, and air conditioning (HVAC) systems, except two classrooms without mechanical ventilation. Classroom attributes, student attendance and school-level ethnicity, gender, and socioeconomic status (SES) were included in multivariate modeling. Forty-five percent of classrooms studied had short-term indoor CO_2 concentrations above 1000 parts-per-million (ppm). A 1000 ppm increase in dCO_2 was associated ($p < 0.05$) with a 0.5% to 0.9% decrease in annual

average daily attendance (ADA), corresponding to a relative 10% to 20% increase in student absence. Annual ADA was 2% higher ($p < 0.0001$) in traditional than in portable classrooms.

Practical Implications

This study provides motivation for larger school studies to investigate associations of student attendance, and occupant health and student performance, with longer term indoor minus outdoor carbon dioxide concentrations and more accurately measured ventilation rates. If our findings are confirmed, improving classroom ventilation should be considered a practical means of reducing student absence. Adequate or enhanced ventilation may be achieved, for example, with educational training programs for teachers and facilities staff on ventilation system operation and maintenance. Also, technological interventions such as improved automated control systems could provide continuous ventilation during occupied times, regardless of occupant thermal comfort demands.

Keywords

carbon dioxide, schools, children, ventilation, attendance

Introduction

Existing information on the relationships between indoor air and environmental quality (IEQ) in classrooms and student absence, health, or academic performance is limited and has been reviewed by Heath and Mendell (2002) and Daisey et al. (2003). There have been a few studies of the associations of student health, and to a lesser extent student absence or learning, with types of ventilation system, ventilation rates, indoor temperature and humidity, concentrations of chemical and microbiological pollutants, and amount of daylight (Pepler, 1968; Green, 1974, 1985; Norback et al., 1990; Ruotsalainen et al., 1995; Myhrvold et al., 1996; Myhrvold and Olsen, 1997; Smedje et al., 1997; Walinder et al., 1997a, 1997b, 1998; Meyer et al., 1999; Ahman et al., 2000; Smedje and Norback, 2000, Kim et al., 2002; Sahlberg et al., 2002; Heschong 2002). Some, but certainly not all, studies have found measured IEQ parameters were associated with health, performance, or absence.

Total ventilation, a combination of unintentional air infiltration through the building envelope, natural ventilation through open doors and windows, and mechanical ventilation, provides a means for reducing indoor concentrations of indoor-generated air pollutants. Ventilation standard 62 developed by ASHRAE (2001) specifies a minimum ventilation rate of 7.5 L s^{-1} (15 ft^3 min^{-1}) per occupant for classrooms. Ceiling- or wall-mounted heating, ventilation and air conditioning (HVAC) systems are often used to mechanically ventilate classrooms, although these HVAC systems may provide less ventilation than intended due to design and installation problems, poor maintenance, and because HVAC systems are often not operated continuously during occupancy.

Since measuring the actual ventilation rate is expensive and potentially problematic, the indoor concentration of carbon dioxide (CO_2) has often been used as a surrogate for the ventilation rate per occupant, including in schools (e.g., Lee and Chang, 1999). Indoor CO_2 concentrations exceed outdoor concentrations due to the metabolic production of CO_2 by building occupants. For example, for adult office workers, assuming a ventilation rate of 7.5 L s^{-1} per person and a typical outdoor CO_2 concentration of 350-400 parts-per-million (ppm), a steady state indoor CO_2 concentration of 1000 ppm has been used as an informal dividing line between "adequate" and "inadequate" ventilation (ASHRAE, 2001). However, a CO_2 concentration is only a rough surrogate for ventilation rate, primarily because the measured concentration is often considerably less than the steady state concentration. Despite the limitations of CO_2 concentrations as a measure of ventilation rate, higher concentrations have been associated with increased frequency of health symptoms and increased absence in studies of office workers (Erdmann et al., 2002; Milton et. al 2000). Available data have indicated many classrooms with ventilation rates below the code minimum or with CO_2 concentrations above 1000 ppm (e.g., Lagus Applied Technologies, 1995; Carrer et. al, 2002; Daisey et al., 2003; RTI, 2003; Shendell et al., 2003a). Therefore, the extent to which lower ventilation rates affect student health, absence, and performance is of particular interest. In general, school absenteeism can serve as an indicator of the student or teacher's overall health condition, although attendance patterns result from a complex interaction of many factors (Weitzman, 1986; Alberg et al., 2003).

This paper presents the results of a study which expanded the work of Prill et al. (2002), who reported findings from rapid IEQ assessment surveys in public schools, including short-term CO_2 measurements in the indoor air, outdoor air, and HVAC supply air diffuser. The present study's hypothesis explored if higher indoor minus outdoor CO_2 concentrations (dCO_2) were associated with increased student absence.

Methodology

Recruitment of classrooms

Primary and secondary schools in the states of Washington (WA) and Idaho (ID) were approached in the 2000-01 and 2001-02 school years to participate in the Washington State University (WSU) and the Northwest Air Pollution Authority (NWAPA) "3 Step IEQ Program," a streamlined approach for implementing the U.S. EPA's *"Tools for Schools"* program (Prill et al., 2002). These schools had attended IEQ workshops conducted by WSU or NWAPA, had contacted WSU or NWAPA for IEQ assistance, or were recommended to WSU and NWAPA by other participant school districts (SDs). To select our sample of schools from this group of K-12 schools (n=224), we used a two-step process. First, we only considered primary schools serving K-5 or K-6 (n=134), excluding special education and day care buildings. Second, due to limited resources and travel logistics, we focused on: 1) schools in cities or SDs with the most primary schools; 2) schools where the majority of classrooms were served by individual HVAC systems (or none if just wall heaters were used); and, 3) schools from which daily attendance data, at the student or classroom level, were available. Individual HVAC systems included wall- and ceiling-mounted unit ventilators or heat pumps for heating and/or air conditioning. We excluded classrooms in buildings where one HVAC system served multiple classrooms and classrooms with unvented space heaters for permanent heating systems. The goal of the selection criteria and exclusion policy was to ensure, to the extent possible, the classrooms including attic spaces were physically separated, with each served by their own mechanical HVAC system, and the environmental measurements conducted in each classroom were independent observations. The final study sample, after some schools could not participate because they lacked appropriate attendance data records, and given available resources, consisted of 436 classrooms from 22 schools (14 in WA, 8 in ID) in 6 SD (4 in WA, 2 in ID).

IEQ Assessments and CO_2 measurements

The IEQ assessments performed in every classroom consisted of walk-through surveys conducted by a technician together with relevant facilities and administrative staff, and short-term measurements of CO_2 during school hours (Prill et al. 2002). CO_2 measurements were conducted by WSU field technicians using the Q-TRAK Model 8551 instrument (TSI, Inc., Shoreview, MN, USA). Inside each classroom, two short-term measurements, each no more than a five-minute average, were conducted sequentially and the measurement times were recorded. First, indoor air CO_2 was assessed near the center of the classroom at the breathing zone height of seated students, but at least one meter from students and not directly underneath the supply air diffusers. Second, the CO_2 concentration in the HVAC supply air was measured using a capture hood to direct undiluted supply air into the instrument sensor. CO_2 instruments were calibrated weekly according to manufacturer specifications using "zero" (N_2, 99.99% pure) and "span" (2010 ppm CO_2, +/- 2%) gases. Instruments were also cross-compared during short-term (< five-minute average) outdoor air CO_2 measurements at each school at locations distant from potential CO_2 sources.

Attendance data

Attendance data were collected from school administrative staff who allowed field technicians access to school attendance records to enter data into a pre-formatted spreadsheet program. For seven schools of one SD, the enrollment and attendance of each individual student on each school day was recorded. For schools in every other SD, we recorded the number of students enrolled, the number absent, and the number in attendance for each classroom and school day. The daily percentages of students in attendance were calculated by pre-coded formulae. Attendance data received a quality control review by LBNL after WSU field technicians sent computer files. This process verified "0" or "blank" (student present) or "1" (student absent) was entered into every cell, vacation periods were left blank, file name room number and grade level designations matched those on the worksheet, and changes in enrollment during the school year were noted with gray-shaded cells. The average daily attendance (number of students attending class divided by number of students enrolled, then converted to a percentage) was calculated for the entire school year and is denoted by "annual ADA" or "yearly ADA." In addition, the same parameter was calculated for the portion of the school year prior to the IEQ inspection and is denoted "pre-visit ADA" or "pre-visit attendance." Although the pre-visit ADA was based on less data than the annual ADA, it was also not affected by any post-inspection ventilation rate changes motivated by recommendations of the inspectors. Annual average absence was calculated as unity minus annual ADA.

Demographic and Socio-economic Variables

Aggregate data were collected on demographic and socio-economic variables that could influence student absence and, thus, confound the study findings. These data were obtained for the 2001-02 school year or based on the 2000 national census data available from several public electronic resources*. Ferris et al. (1988) reported data on gender and age (grades) helped explain observed variance in absenteeism. Haines et al. (2002) found the percentage of students in a grade level eligible for subsidized (free) meals at school was related to the average socio-economic status (SES) of the school enrollment in that grade. We collected data, at the school level, on gender and ethnicity (five categories). We also collected school-level data on percent participation in subsidized free lunch programs, reduced-cost lunch programs, and the composite of the free and reduced-cost lunch programs; the composite was used as an indicator of student SES.

* ID Department of Education (*http://www.sde.state.id.us*); WA Office of the Superintendent for Public Instruction (*http://www.k12.wa.us/edprofile*, *http://www.k12.wa.us/* OSPI Programs child nutrition, data administration, demographics, statistics); National Center for Educational Statistics (*http://nces.ed.gov/ccd/schoolsearch*).

CO_2 metric

Based on the measured CO_2 data, we computed the difference between the measured indoor and outdoor CO_2 concentrations (dCO_2). Previous research on CO_2 in school classrooms (Fox et al., 2003) demonstrated a single monitoring location was appropriate for characterizing such indoor contaminant levels when HVAC systems were on, i.e., air was well-mixed. The dCO_2 is only a rough surrogate for ventilation rate because it is based on one-time short-term measurements made at a wide range of times throughout the school day. The major advantage of dCO_2, relative to a ventilation rate estimate, is dCO_2 does not rely on any other assumptions. We made a thorough attempt to use the measured indoor CO_2 concentration and measurement time data to estimate the total ventilation rate, the flow rate of outside air into the classroom on the day of the CO_2 measurement prior to the measurement, by applying the transient mass balance equation. This approach, however, required several assumptions to be made, including for the calculation of the student indoor CO_2 generation rate, which varied by age (grade) and activity level. For details and related results, readers are referred to this study's final report available to the public through LBNL (Shendell et al., 2003c).

Multivariate Analyses

The data were analyzed with SAS software (Enterprise Guide version 1.3 and SAS system release 8.2, SAS Institute, Cary, NC). Descriptive statistics were calculated and the associations of independent variables with student attendance or absence were determined using multivariate linear regression models (ANOVA, PROC GLM). Models were developed for annual ADA, pre-visit ADA, and annual average absence as dependent variables. Independent variables in the final models were: 1) dCO_2, as a continuous variable; 2) the composite percentage of students at a school participating in subsidized free and reduced-cost lunch programs as an indicator of student and family SES; 3) grade level; 4) type of classroom – traditional or portable; 5) the state in which the classroom was located; and 6) the percentages of Hispanic and/or White/Caucasian students in the school as indicators of ethnic composition. Ideally, since multivariate linear regression requires observations to be independent, data on the SES indicator variable and the race/ethnicity variable at the classroom level instead of at the school level would have been preferred. This unavoidable limitation of the study's database was due to both the retrospective nature of attendance and potential confounder data collection and, more importantly, the reality that participant SDs only release these types of demographic data for public use at the school level due to confidentiality issues and political sensitivities. Nevertheless, visits to the SDs suggested variability within schools was much less than between schools for these two potential confounder variables.

Depending on the terms in the model, certain data were excluded because the values of one or more input parameters were missing. The two classrooms in WA with no mechanical HVAC system and the five classrooms with students in more than one grade level were excluded.

Results

Descriptive Statistics

The average primary school was about 45 years old and most (94%) classrooms were in the main building, i.e., traditional, not portables. There was a fairly equal distribution of classrooms visited across the seven grades except 6th grade classrooms were visited relatively less often because many primary schools in our study only included K-5th grades (Table 1, see page 10). Visits to study classrooms were fairly well distributed throughout the school day, although the least number of visits occurred during unoccupied periods (Table 1). Overall, about 19 of every 20 classrooms in this study were found with the HVAC system on or cycling automatically between on or off. About nine of every 10 classrooms visited were found with windows to the outside closed. In this study, 45% of visited classrooms had measured short-term indoor CO_2 concentrations above 1000 ppm (59% in ID and 35% in WA). Across states, grades, and room types, the geometric mean annual absence was 5% (median 4.9%, arithmetic mean 5.2%); the mean and median annual ADA were 95%.

Table 2 (page 11) presents descriptive statistics for dCO_2 and ADA by state and room type. In ID, the average, median, minimum, and estimated 90th percentile dCO_2 values were higher in portable than traditional classrooms. In WA, average dCO_2 was slightly higher and maximum and estimated 90th percentile values were higher in portable than traditional classrooms; however, the median and minimum values were higher in traditional than portable classrooms. Average and median values for "yearly" and "pre-visit" ADA, which were similar, were higher in traditional than portable classrooms, slightly higher in ID than WA traditional classrooms, and higher in WA than ID portable classrooms.

Table 3 (page 12) summarizes descriptive statistics for selected short-term CO_2 measures and attendance data by state, room type, and school to provide insight into within-school versus between-school variability. Within-school variability was evaluated by examining the standard deviations and ranges (minimum-maximum) of measured values. Between-school variability was evaluated by comparing the average and median values, and the ranges of measured values. The study data suggested considerable variability within most schools across states and room types, especially in ID, where ranges of dCO_2 values were generally higher. Across states among traditional classrooms, and WA portables, the data again suggested variability in dCO_2 values. For ID portables, the average and median values were similar between schools, though minimum and maximum values differed, likely due to small sample sizes (two schools, 3-4 classrooms at each). Across states and room types, the data suggested variability in annual ADA between schools since the ranges of average and median values, which were similar, were 2-4%. Idaho portables showed relatively more variability between schools, which again may be due to small sample sizes. Across states and room types, the data also suggested variability in annual ADA within most schools, and relatively more so in WA than in ID among traditional classrooms.

Table 4 (page 13) presents descriptive statistics for dCO_2 by state, grade level (age), and room type. Across grades, average dCO_2 values were higher for traditional than portable classrooms in WA except for grade four, in part due to the small sample size of portables. In ID, average dCO_2 values were higher in portable than traditional classrooms across grades, and median dCO_2 values were similar across grades 1-6, which were higher than for kindergarten classrooms. In WA traditional classrooms, median dCO_2 values increased from kindergarten through grade six, except for a decrease at grade five. Across states and room types, except in WA grade 1 and grade 2-3 traditional classrooms and in WA portables for kindergarten and grades 2 and 3, where there were usually small sample sizes, maximum dCO_2 values were greater than 1000 ppm.

Furthermore, dCO_2 and short-term indoor CO_2 measurements in ID grade two portables were always above 1000 ppm. Overall, these observations on Table 4 were likely in part related to occupant densities and the ages of students as related to CO_2 generation rates (Shendell et al., 2003c), given WSU visits were spread across grades and school day hours (Table 1). Uncertainty included operations and maintenance practices at participating schools. Finally, by state, grade, and room type, variability in attendance and absence data (not presented) was observed as expected due to multiple factors such as susceptibility to illness by age, climatic conditions by season, sample sizes, and factors related to absence not assessed in this study.

Results of Multivariate Analyses

The primary results of the multivariate modeling are provided in Table 5 (page 14). The final models included the most important variables, which were entered into the model at once (not stepwise), after examination of possible correlation between specific independent variables. The dCO_2 variable was statistically significantly ($p < 0.05$) associated with both the annual ADA and with the pre-visit ADA. For annual ADA, the parameter estimate indicated a 0.5% absolute decrease in attendance, corresponding to a 10% relative increase in the average 5% absence rate, per 1000 ppm increase in dCO_2. For the pre-visit ADA, the parameter estimate indicated a 0.9% absolute decrease in attendance, corresponding to a relative 20% percent increase in the average 5% absence rate, per 1000 ppm increase in dCO_2.

The traditional classroom type, relative to a portable classroom, was associated with approximately a 2% increase in attendance, and with a 2.5% decrease in absence. In each case, the associations were statistically significant ($p < 0.01$).

A one percent increase in the SES variable, representing the percentage of students receiving free or reduced cost lunch, was associated ($p < 0.001$) with a 0.03% to 0.04% decrease in attendance, and with a 0.02% increase in absence ($p < 0.001$). A one percent increase in the percent of Hispanic students was associated ($p < 0.02$) with a 0.03% increase in attendance, and with 0.05% decrease in absence ($p < 0.001$).

In most models, the state variable was not associated with attendance and the corresponding parameter estimate was unstable (results not included in Table 5). The most likely explanation for these findings was the present study only included two states.

Discussion

In this study, 1000 ppm increases in the difference between indoor and outdoor CO_2 concentrations were associated with 10% to 20% relative increases in student absence, and the associations were statistically significant. These findings of this study are generally consistent with those of Milton et al. (2000), who found a 50% reduction in ventilation rates in offices, with corresponding increases in indoor CO_2 concentrations, was associated with a 50% increase in short term absence among the office workers occupying the buildings. One potential explanation for our findings and those of Milton et al. (2000) is lower rates of ventilation, indicated by higher CO_2, caused increased communicable respiratory illnesses, probably by increasing the indoor concentration of airborne infectious particles produced during coughing or sneezing. In a review of the literature, Fisk (2000) summarized three studies reporting a reduction in ventilation rate was associated with increases in confirmed respiratory illness.

Because the CO_2 measurements in this study were short-term, five-minute, measurements made on a single school day at variable times of day, they should be considered only rough surrogates for the long-term average classroom ventilation rates that may affect long-term average absence rates. In general, random errors** in an independent variable, in this case the errors from using short-term CO_2 as a measure of long-term average ventilation rate, will tend to obscure and weaken associations with the dependent variable (in this case, attendance or absence).

We are not aware of large uncontrolled sources of bias likely to create erroneous associations of higher dCO_2 concentrations with increased absence. The models contain variables controlling for SES, classroom type, grade level, ethnic composition, and the State in which the classrooms are located. Thus, we have controlled as well as possible, given data resources available to the American public, for obvious sources of confounding bias. However, it is still possible some unknown classroom factor, which increases absence rates, is positively correlated with the measured classroom CO_2 concentrations.

This study confirms previous findings of high CO_2 concentrations in classrooms, which indicated classroom ventilation rates were often below the minimum rates specified in codes. In this study, almost half of the CO_2 concentrations were above 1000 ppm and 4.5% were above 2000 ppm. If the measured CO_2 concentrations had been maximum or steady state values, a substantially larger proportion would be expected to exceed 1000 ppm. Thus, it is likely more than half of the classrooms in this study had ventilation rates less than specified in current minimum ventilation standards.

The substantially higher rate of absence in portable classrooms,

*** Errors that are not correlated with the value of the dependent varialbe.*

relative to traditional classrooms, is notable. We do not have a clear explanation for this finding. It is not known whether portable classrooms have inferior IEQ relative to traditional classrooms. Recent evidence in Los Angeles County, however, has suggested relatively higher indoor air concentrations of toxic and odorous volatile organic compounds are possible in portable classrooms (Shendell et al., 2003b), as are higher occupant densities even if federal and state class size reduction initiatives apply across room types. In addition, it is not known whether inferior IEQ could cause such a large increase in absence. Although the higher absence rate in portable classrooms was statistically significant, the small sample (25 classrooms) should be considered. Before drawing conclusions, other studies should compare absence rates in portable and traditional classrooms.

Finally, we note how changes in ventilation or in any other factor affecting student attendance will influence the funding provided to many SDs, because funding is linked to annual ADA. For example, in California the most currently available (2001-02) funding rate is $12.08 per student-day not absent (CDE, 2003). For a classroom of 20 children with a 185-day school year (3700 student-days), a 1% decrease in annual ADA (or 20% relative increase in absence) is $450 per classroom in funding lost to the SD.

Conclusions

The major findings of this study were as follows:

- A 1000 ppm increase in the elevation of the indoor CO_2 concentration above the outdoor concentration was associated ($p < 0.05$) with a 0.5% to 0.9% decrease in yearly attendance, corresponding to a relative 10% to 20% relative increase in student absence.
- Yearly attendance was 2% higher ($p < 0.0001$) in traditional than in portable classrooms.
- Based on the measured CO_2 concentrations, we estimated ventilation rates in at least 50% of the classrooms were less than 7.5 L s^{-1} per person, which is the minimum rate specified in most codes and standards.

Since this study was based on analyses of previously collected CO_2 data, general conclusions should not be drawn from the observed linkage of higher CO_2 levels with increased absence. This study, however, does provide motivation for larger studies designed specifically to investigate the linkage of longer term CO_2 concentration data and more accurately measured ventilation rates with student absence.

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Table 1:
Summary statistics of frequency of observations for selected qualitative variables.

Values presented are number of observations and percentage of observations (%).								
Time of visit and measures: school schedule variable*								
	Early AM	AM recess	Late AM	Lunch	Early PM	PM Recess	Late PM	Not Known
Overall study	85 (21.2%)	9 (2.2%)	90 (22.4%)	39 (9.7%)	123 (30.7%)	11 (2.7%)	44 (11.0%)	35
WA only	23 (9.0%)	4 (1.6%)	68 (26.7%)	32 (12.6%)	93 (36.5%)	7 (2.8%)	28 (11.0%)	9
ID only	62 (42.5%)	5 (3.4%)	22 (15.1%)	7 (4.8%)	30 (20.6%)	4 (2.7%)	16 (11.0%)	26
Grade (K, 1st to 6th)								
	K	1st	2nd	3rd	4th	5th	6th	Other**
Overall study	64 (14.8%)	70 (16.2%)	68 (15.7%)	67 (15.5%)	57 (13.2%)	61 (14.1%)	41 (9.5%)	8 (1.2%)
WA only	38 (14.6%)	43 (16.5%)	43 (16.5%)	41 (15.7%)	34 (13.0%)	38 (14.6%)	19 (7.3%)	8 (2.0%)
ID only	26 (15.1%)	27 (15.7%)	25 (14.5%)	26 (15.1%)	23 (13.4%)	23 (13.4%)	22 (12.8%)	0

* The values presented for this variable were coded as the categorical 1-7 (“.” for not known) for statistical analyses in SAS Enterprise Guide v.1.3 (SAS v.8.2, Cary, NC).

** “Other” meant the classroom was occupied by students in multiple grades (2nd and 3rd) or the grade level varied and was not documented.

Table 2:
Descriptive statistics for selected measures, with results presented by state and room type.

dCO$_2$ (ppm), the short-term indoor minus school outdoor CO$_2$ concentration									
State	Room type*	No. Class-rooms	No. Obs. (No. Missing obs.)	Average	Median	Std Dev	Min	Max	Est. 90th %tile
ID	M	165	164 (1)	840	670	630	50	4230	1460
ID	P	7	7	1510	1590	790	110	2440	2440
WA	M	244	239 (5)	580	570	310	60	3030	890
WA	P	18	16 (2)	610	300	850	10	3510	1140
Annual average ("yearly") daily attendance (as %)**									
State	Room type*	No. Class-rooms	No. Obs. (No. Missing obs.)	Average	Median	Std Dev	Min	Max	Est. 90th %tile
ID	M	165	165	95.3	95.5	1.5	85.2	97.9	96.6
ID	P	7	7	91.0	92.4	3.5	87.0	95.1	95.1
WA	M	244	244	94.6	94.8	1.5	88.9	98.6	96.4
WA	P	18	18	93.3	93.4	1.7	89.8	97.0	95.1
Average "pre-visit" daily attendance (as %)									
State	Room type*	No. Class-rooms	No. Obs. (No. Missing obs.)	Average	Median	Std Dev	Min	Max	Est. 90th %tile
ID	M	165	165	95.4	95.6	1.6	83.5	98.0	96.9
ID	P	7	7	90.4	93.0	4.6	84.7	95.0	95.0
WA	M	244	244	95.3	95.3	1.9	88.6	99.0	97.6
WA	P	18	18	93.9	93.6	2.0	90.8	98.3	96.5

* M = main building/traditional classroom, P = portable/relocatable classroom

** Annual average ("yearly") daily absence (as %) was calculated as 1 - "yearly" daily attendance (as %).

NOTE: WSU technicians did not record room type for two WA classrooms, thus were excluded.

Table 3:
Descriptive statistics for selected measures, with results presented by state, room type and school to provide insight into within-school versus between-school variability.

					dCO_2, short-term indoor minus school outdoor school outdoor						Annual average ("yearly") daily attendance***						
State	Room Type*	School	No. Class-rooms **	No. Obs. (No. Miss obs.)	Average	Median	Std Dev	Min	Max	Est. 90th %tile	Average	Average	Median	Std Dev	Min	Max	Est. 90th %tile
ID	M	A	11	11	1070	1190	480	310	1790	1590	410	94.1	94.0	1.0	92.2	96.2	94.9
		B	23	23	560	550	310	70	1200	970	380	95.7	96.0	1.0	93.3	97.0	96.6
		C	21	21	480	460	180	70	840	680	400	94.9	94.9	0.9	92.9	96.4	95.9
		D	23	23	1000	980	380	400	1630	1560	360	95.2	95.9	3.1	85.2	97.7	97.4
		E	20	20	510	340	540	50	2450	980	350	95.4	95.6	0.9	92.7	96.5	96.4
		F	26	25 (1)	590	610	280	180	1190	1060	450	96.0	95.9	0.7	94.9	97.9	96.7
		G	25	25	1670	1410	930	460	4230	3370	380	95.3	95.4	1.0	92.1	96.7	96.4
		H	16	16	810	720	250	550	1390	1320	400	94.9	94.8	0.9	93.4	96.6	96.1
ID	P	A	3	3	1540	1590	230	1290	1740	1740	410	93.2	93.0	0.9	92.4	94.1	94.1
		D	4	4	1500	1720	1100	110	2440	2440	360	89.3	87.6	3.9	87.0	95.1	95.1
WA	M	I	9	9	710	410	890	110	3030	3030	390	92.7	93.0	1.2	90.8	94.0	94.0
		J	16	16	810	790	120	610	1060	960	440	95.3	95.4	1.1	93.2	96.7	96.6
		K	14	14	440	400	150	210	710	680	380	94.1	94.5	1.3	90.0	96.0	95.0
		L	17	17	440	430	220	200	870	820	390	95.1	95.1	0.7	93.9	96.0	96.0
		M	19	19	460	410	200	150	1010	710	370	94.7	94.8	1.8	91.9	98.6	97.5
		N	20	16 (4)	570	530	270	130	1030	930	380	95.0	95.1	1.2	92.4	96.8	96.5
		O	13	13	560	630	290	60	1080	880	370	95.5	95.6	1.7	90.3	97.1	96.8
		P	22	22	460	500	210	130	1030	590	370	95.8	96.2	1.0	93.1	97.0	96.7
		Q	16	15 (1)	390	360	250	110	900	800	380	94.3	94.3	1.2	92.3	96.1	95.9
		R	24	24	670	600	210	370	1130	1020	380	94.1	94.4	1.6	88.9	95.8	95.5
		S	23	23	660	650	150	450	980	880	380	94.9	95.2	1.3	92.1	96.7	96.2
		T	20	20	690	680	140	400	910	870	360	93.9	93.8	1.2	90.9	96.3	95.3
		U	13	13	550	620	230	190	970	740	360	94.2	94.4	1.5	91.6	96.5	96.1
		V	18	18	690	500	540	260	2060	2010	350	94.2	94.7	1.5	90.8	96.9	96.2
WA	P	I	4	4	960	170	1700	10	3510	3510	390	91.9	92.0	1.6	89.8	93.8	93.8
		K	3	3	400	460	110	270	460	460	380	92.3	91.8	1.2	91.5	93.7	93.7
		L	2	2	330	330	250	160	510	510	390	94.8	94.8	0.4	94.5	95.0	95.0
		P	2	2	250	250	40	220	280	280	370	94.8	94.8	3.1	92.6	97.0	97.0
		S	2	2	990	990	120	910	1080	1080	380	94.4	94.4	0.1	94.3	94.4	94.4
		T	3	3	530	320	540	130	1140	1140	360	92.3	92.3	0.8	91.6	93.1	93.1

* M = main building/traditional classroom, P = portable/relocatable classroom

** Enrollment, attendance and absence data were available for each classroom included in analyses presented on this table.

*** Annual average ("yearly") daily absence (as %) was calculated as 1 - "yearly" daily attendance (as %).

Table 4:
Descriptive statistics for dCO_2 (in ppm) by state, grade level (age), and room type.

State	Grade	Room Type*	No. Class-rooms**	Arithmetic Mean	Median	Standard Deviation	Minimum	Estimated 90th Percentile	Maximum
ID	K	M	26	570	440	410	70	1320	1410
WA	K	M	35	500	430	470	200	770	3030
WA	K	P	2	250	250	40	220	280	280
ID	1	M	27	820	680	480	250	1780	2130
WA	1	M	42	470	430	210	120	750	890
ID	2	M	22	1160	700	1030	210	2680	4230
ID	2	P	3	1540	1590	230	1290	1740	1740
WA	2	M	42	580	560	330	150	860	2060
WA	2	P	1	270	270	n/a3	270	270	270
ID	3	M	26	910	780	730	70	1430	3370
WA	3	M	40	600	610	320	60	880	2010
WA	3	P	1	460	460	n/a***	460	460	460
ID	4	M	23	790	680	520	50	1460	2290
WA	4	M	32	680	660	190	210	920	1010
WA	4	P	2	1980	1980	2160	460	3510	3510
ID	5	M	23	900	690	540	110	1680	2450
WA	5	M	33	580	570	240	110	920	1080
WA	5	P	5	410	320	410	10	1080	1080
ID	6	M	18	730	690	290	220	1130	1190
ID	6	P	4	1500	1720	1100	110	2440	2440
WA	6	M	14	810	760	150	650	1020	1130
WA	6	P	5	500	280	490	60	1140	1140
WA	2 and 3	M	2	610	610	400	330	890	890
WA	4 and 5	M	3	770	690	440	370	1240	1240

* M = main building/traditional classroom, P = portable/relocatable classroom

** Short-term indoor CO_2 (and thus dCO_2) data were missing for the following numbers of classrooms (n=6 total): grade 2, WA, M (n=1); grade 4, ID, M (n=1); grade 4, WA, M (n=1); and, grade 5, WA, M (n=3).

*** n/a = not available because of small sample size (only one classroom) in this strata

Table 5.
Key results of multivariate regression modeling.*

Basic Model Characteristics				CO_2 (per ppm)		Room Type Variable **		SES Variable ***		Ethnicity Variable ****	
No. Class-rooms	Atten-dance or Absence Variable	CO_2 or Vent. Rate Vari-able in Model	Model R_2	Para-meter Estimate	P-value	Para-meter Estimate	P-value	Para-meter Estimate	P-value	Para-meter Estimate	P-value
395	Yearly Atten-dance%	dCO_2	0.21	-0.0005	0.02	2.29	<0.001	-0.026 0.0003	--	0.026	0.001
395	Pre-visit Atten-dance%	dCO_2	0.18	-0.0009	0.001	2.33	<0.001	-0.037 <.0000*	--	0.029	0.02

* Parameter estimates represent percent increase in attendance or absence per ppm CO_2, 1 m^3 s^{-1} ventilation rate; or percent increase in the SES or ethnicity variable, or for a traditional classroom relative to a portable classroom. The P-values for the total model were always < 0.0001.

** For traditional/main building classrooms relative to portable/relocatable classrooms.

*** The variable represented the percentage of students at the school receiving either free or reduced lunches.

**** Percent Hispanic, in some models percent white/Caucasian was also included and significantly associated with attendance.

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THE ROLE OF BUILDING VENTILATION AND FILTRATION IN REDUCING RISK OF AIRBORNE VIRAL TRANSMISSION IN SCHOOLS, ILLUSTRATED WITH SARS-COV-2

Indoor Air Quality Section
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California Department of Public Health

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Summary

Long-range airborne transmission of multiple infectious diseases within buildings has been well documented. Growing evidence suggests that transmission by small airborne particles (aerosols) may also be an important route for SARS-CoV-2, the virus causing the novel coronavirus disease COVID-19, especially in enclosed environments with poor ventilation and high occupant density. This paper presents an interactive tool, based on existing risk-estimation models, that calculates the effects of classroom ventilation rates and filtration efficiency, as well as wearing masks, on the relative risk of long-range airborne transmission. We demonstrate the model using an example of the current COVID-19 pandemic in a hypothetical classroom setting with one asymptomatic infected individual. We model five scenarios representing a range of ventilation rates potentially encountered in California schools, including a “no ventilation” scenario. We quantify, with respect to the risk of infection by long-range small aerosols, the expected relative risk reductions that could be achieved with different improvements in ventilation and air filtration. For all modeled ventilation rates, the relative risk of infection was lowest with use of both an enhanced air filtration method (either a MERV 13 filter or portable air cleaners) and face masks. We discuss the potential that improved classroom ventilation and filtration strategies offer for reducing the spread of COVID-19 in particular and note the potential for enhanced ventilation to provide broader health benefits for those in the classroom.

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Practical Implications

Based on our modeling assumptions and results, protective strategies that can substantially reduce the risk of long-range airborne transmission of SARS CoV-2 in classrooms include:

- Mask wearing: Teachers and students should wear masks – this practice reduces this risk by more than half, regardless of the rate of ventilation or filtration of air in the classroom.

- Outdoor air ventilation: The ventilation system should provide at least the California Title 24 code-required minimum ventilation rate. Note that if there was *no ventilation* and *no filtration*, the risk of long-range airborne infection would be *over six times as high as* that for a classroom with code-required ventilation and a MERV 8 filter.

- Filtration: Ventilation system filters should be MERV-rated (e.g., MERV 13 or better) as well as properly installed (i.e., no gaps that would allow air to bypass the filter) and filters should be properly maintained (i.e., replaced as often as recommended). MERV-rated filters can provide substantial protection, especially if ventilation is poor.

- In-room (portable) air cleaners: Devices, with high efficiency filtration, can provide substantial additional protection, especially in naturally ventilated classrooms (those in which air is supplied only through open windows or doors) or in classrooms with non-functioning or poorly functioning ventilation systems, if the clean air delivery rate (CADR) is sufficient (i.e., at least 2/3 of the floor area). Multiple devices per classroom may be necessary.

Do not use air cleaning devices that generate harmful pollutants (i.e., ionization devices or ozone generators), or devices of unproven effectiveness.

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Airborne transmission of infectious respiratory viruses and the potential role of ventilation in reducing exposure

The three primary modes of possible transmission of infectious respiratory viruses are: (1) short-range exposure to large and small respiratory droplets that people release when breathing, speaking, singing, coughing, or sneezing; (2) contact with surfaces that have been contaminated through touch or droplet deposition (fomites), such as doorknobs or desktops, and viral transfer to the nose, mouth, or eyes; and (3) long-range airborne transmission through inhalation of smaller, virus-containing aerosols (Figure 1).[1]

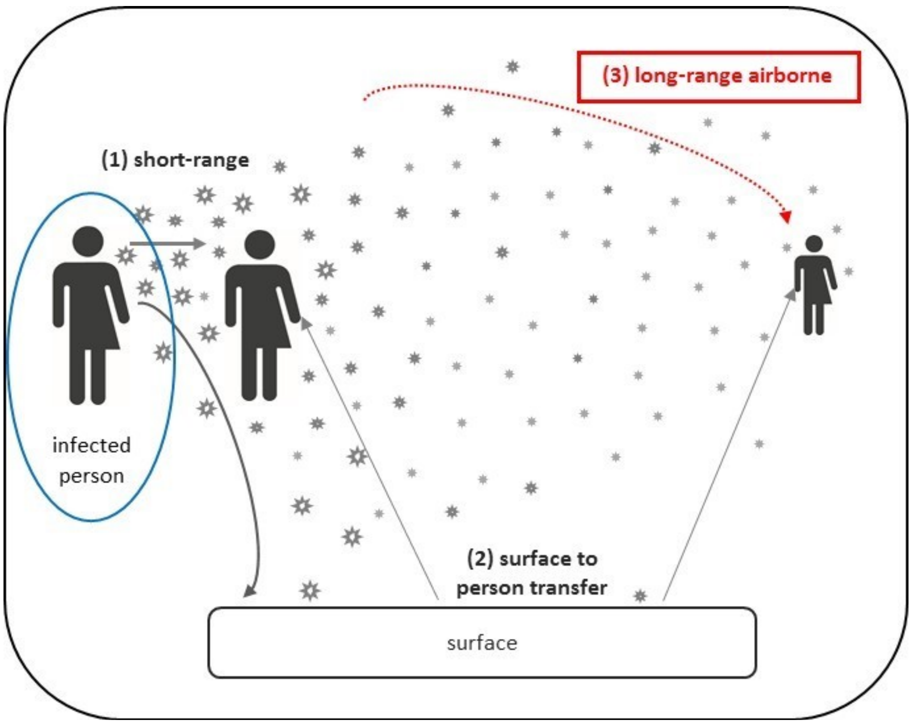


Figure 1. Routes of transmission from a case to a susceptible individual: (1) short-range, small and large respiratory droplet exposure, (2) surface contact, and (3) long-range airborne transmission. The figure shows how a susceptible person can encounter aerosols in a range of sizes if sufficiently close to an infected person; the larger particles settle out of the air, but the smaller particles can remain airborne, accumulate, and travel farther from the infected person.

Researchers, in considering routes of viral exposures in the current pandemic, now question the common assumption that emitted infectious particles can be divided neatly into two size categories: *large droplets* that directly reach another person or fall quickly to the ground and *small droplets* (that dry to droplet nuclei) that remain airborne. In fact, respiratory droplets are known to be generated in a continuum of sizes by normal breathing, speaking, and throat clearing as well as by explosive emissions from sneezing and coughing.[2-9] This paper focuses on "long-range airborne transmission by small aerosols," or more briefly, "airborne transmission." We define this as disease transmission involving the range of particle or droplet sizes sufficiently small to remain suspended in air for minutes to hours, thus allowing them to *accumulate over time* in enclosed spaces and to *travel long distances* from the infected person who generated them (route 3 in Figure 1). We note that different fields use different terminology, e.g., aerosol, droplet, particle, or airborne agent. In this paper, which cites evidence from many sources, we use several terms interchangeably to refer to respiratory particles that may contain SARS-CoV-2.

Evidence for airborne transmission of SARS-CoV-2

The World Health Organization (WHO) and the U.S. Centers for Disease Control and Prevention (CDC) have stated that, according to current evidence, SARS-CoV-2, the virus that causes the current pandemic disease COVID-19, is transmitted primarily from person to person. By this they mean through either short-range, large and small respiratory droplets or contaminated fomites[10-12] (routes 1 and 2 in Figure 1). These transmission mechanisms and appropriate control/prevention strategies are addressed in published guidance on reducing disease transmission in schools during this pandemic.[13-15] At first, these organizations recognized only limited specific procedures or treatments, primarily in medical settings, as generating small aerosols that could spread through airborne transmission (route 3 in Figure 1). In July, however, WHO reviewed more recent evidence and concluded that "the role and extent of airborne transmission outside of health care facilities, and in particular in close settings with poor ventilation, also requires further study."[12]

Other organizations and professional groups have stated different positions. The *Standing Committee on Emerging Infectious Diseases and 21st Century Health Threats* found that "currently available research supports the possibility that SARS-CoV-2 could be spread via bioaerosols generated by patients' exhalation," without defining "bioaerosols." The Chinese National Health Commission (NHC) suggested that long-range aerosol transmission may occur in crowded and poorly ventilated enclosures or spaces.[16] A growing number of professionals from diverse fields have argued that airborne transmission is possible in circumstances beyond the limited ones that WHO and CDC originally recognized and that appropriate measure, such as improved ventilation and filtration efficiency, are also needed.[2-6,17-38]

There is both direct and indirect evidence supporting probable long-range airborne transmission. The direct evidence involves research on SARS-CoV-2 (from field studies in environments where the virus is known to be present or experimental aerosol and animal studies with the virus) or review of epidemiologic data from studies of confirmed transmission of COVID-19. The indirect evidence is from knowledge of the virology of respiratory disease agents and modeling of particle movement in indoor spaces. Appendix 1 lists databases of recent research pertaining to this question as well as brief descriptions of studies cited in this paper, not all yet peer reviewed and thus potentially subject to change. Not covered in this review are studies of exposure due to aerosolization of fecal matter;[39,40] although such transmission may occur in school restrooms, and may warrant additional control strategies, the focus of our paper is the classroom environment, where students spend the majority of their time at school. Other guidance documents on school reopening address appropriate precautions regarding ventilation for restrooms and adequate handwashing facilities.[15,41-49]

Direct evidence from field studies includes detection of SARS-CoV-2 in air samples ≥4 m from a COVID-19 patient and on surfaces in patient rooms where large droplet deposition is less likely than small aerosol spread, e.g., under a patient's bed; on a supply or exhaust air vent, outlet, damper, louvre, or grate; and on air outlet filters and fans.[50-57] Aerosol transport may explain these findings, because virus-containing particles were detected in size ranges sufficiently small to remain airborne and travel long distances.[53,58] More convincingly, viral RNA has been recovered within a hospital air handling unit on prefilters (of mixed outdoor and return air), on final filters (after the supply air fan), and on supply air dampers[56] as well as on exhaust filters and the surface of central air ducts up to 56 m from patient areas.[57]

Direct evidence from experimental research has found that SARS-CoV-2, aerosolized and kept suspended artificially in an environmental chamber with a rotating drum, remained viable (i.e., retained replication competence) for up to 16 h.[59,60] SARS-CoV-2 also was more efficiently aerosolized than SARS-CoV and another coronavirus, the causative agent of MERS.[59] Animal studies have demonstrated infection in mice,[61] hamsters,[62-64] ferrets,[65,66] and monkeys[67] with various strains of the SARS-CoV-2 virus via aerosol exposure.[61,67] Infection occurred not only through contact between donor and naïve animals housed together,[62,63,65,68] but also between donor and naïve animals in individual cages separated by a surgical mask or permeable partition.[62,64-66] The latter suggests airborne or droplet transmission over short distances.

Epidemiologic investigation of large and small outbreaks has identified possible airborne transmission of SARS-CoV-2 in crowded or poorly ventilated indoor settings, which may explain some community spread of COVID-19.[69-72] Some have suggested that airborne transmission may explain infection of persons who did not have close or frequent contact with cases,[73] other attendants at meetings,[71,74] passengers on a bus including those seated remotely,[71] and chorus members who reported no physical or close contact.[75] Also, this route has been suggested as a plausible explanation for the documented transmission from asymptomatic or pre-symptomatic cases—i.e., transmission from an infected person with no symptoms through small aerosols emitted by normal breathing or speaking[6,8,17,19,30,76-79]—although transmission by occasional larger respiratory droplets or fomite contact cannot be ruled out in such episodes and in the other examples.[73] In one study, PCR cycle times were similar for symptomatic and asymptomatic, isolated patients, but viral loads in the latter decreased more slowly from time of diagnosis to discharge.[80]

Indirect virologic evidence includes what is known about respiratory disease agents generally and SARS-CoV-2 specifically: (a) other viruses spread as aerosols either primarily or in addition to other routes;[4,17,28,81,82] and (b) the similarity of SARS-CoV-2 to other coronaviruses that are transmitted as aerosols.[4,17,28,81,83]

Additional indirect evidence comes from imaging and size-fractionated air sampling, showing that both symptomatic and healthy persons emit particles from the upper and lower respiratory tracts when breathing, speaking, coughing, and sneezing.[19,20,25,82,84-86] The size distributions include virus-containing small particles that can be distributed readily as aerosols. In one study, the virus was detected in the exhaled breath of COVID-19 patients (16.7 percent, n = 30) more often than on surfaces (5.4 percent, n = 242) or in air samples (and 3.8 percent, n = 26).[87] The single positive air sample was from an unventilated toilet room.

A third line of indirect evidence comes from the modeling of particle dispersion in indoor air, e.g., computational fluid dynamic (CFD) simulations of particle residence times using size distribution data from imaging and air sampling studies. These models demonstrate that the sustained suspension in air of SARS-CoV-2 makes long-range airborne transmission of disease plausible.[4,8,9,69,88-96]

However, there is still dispute in the scientific community about the occurrence and extent of airborne transmission. For instance, an outbreak among three families at separate tables in a restaurant in China has been cited as evidence both for and against airborne transmission.[69,97] Also, transmission did not occur on a 15-hour flight from Guangzhou to Toronto; however, the two infected persons had mild symptoms and wore masks.[98] An initial examination of transmission aboard a cruise ship concluded that the central air conditioning system did not play a role in the spread of the disease because long-range transmission did not occur, and the observed spread could be explained by passenger close contact and fomite transmission within staterooms after a quarantine was imposed.[99] A second analysis concluded that airborne transmission through the ventilation system could explain spread that occurred during the quarantine period because symptomatic infection rates were similar in cabins with and without confirmed cases, the latter included single-occupancy cabins (note: only symptomatic persons were tested during the quarantine period).[100] However, these conclusions are not relevant to central ventilation systems generally because, as a more detailed study of this outbreak pointed out, “cruise ships represent unique built environments with high ventilation rates (VRs) and no air recirculation.”[9] This particular ship provided 100 percent outdoor air, no recirculation, and a very high VR of 9–12 air changes per hour (ACH). This later study, reported in a not yet peer-reviewed modeling paper on the same outbreak, estimated the median contributions of short-range, long-range, and fomite transmission, over multiple models, to be 36 percent, 41 percent, and 21 percent, respectively.[9]

Many have cited the chamber studies discussed above[59,60] as evidence that SARS-CoV-2 can remain suspended in air and infectious for long periods. While replication-competent virus was recovered for up to 3 and 16 hours, the rotating drum used to keep the virus suspended produces conditions unlike typical air movement in buildings. Also, the nebulizer used generates small particles that may not represent the respiratory droplets that humans release, and the chamber temperature and humidity conditions may differ from those generally found indoors.[33,101-103]

Another argument made against airborne transmission is that COVID-19 apparently produces fewer secondary cases in close contacts, even among household members, than other diseases known to be airborne.[5,104,105] The basic reproduction number (R_0) is the average number of other persons that one disease case is likely to infect, in a population with no immunity (from previous infection) and no interventions (social distancing or mask wearing).[106] R_0 is determined by tracing close contacts of cases, and estimates for SARS-CoV-2 range from <1–7, lower than for known airborne infectious agents such as the measles and chickenpox viruses, with R_0 of 9–18 and 2–68, respectively (Appendix 2). However, the current coronavirus's transmissibility is similar to that of SARS-CoV, for which there is evidence of airborne transmission, even though the estimated R_0 for SARS-CoV is only <1–6 (Appendix 2).

To date, few field studies have used culture or other assays to assess viral viability in air,[55,107,108] although studies have documented viable SARS-CoV-2 on contaminated surfaces.[55,60,109] In one of these studies, three viable human respiratory viruses were recovered, but not SARS-CoV-2.[107] Only two of these studies have shown evidence that SARS-CoV-2 was capable of replication.[55,108] In the first study, the large variability in sampling results suggested air concentrations too low to be accurately quantified.[55] In the second, there was a clear progression of virus-induced cytopathic effects in cell culture, the recovered virus could be serially propagated, and the isolated viruses matched that in a newly admitted, symptomatic patient.[108] In addition to issues with detection limits,[110] some air sampling methods and conditions may damage the virus, rendering it nonviable.[51,53,55,101,108,111]

Although viral RNA has been detected in exhaled breath,[72] one study reported that viable SARS-CoV-2 was not detected even when an air sampler was just 10 cm from the chin of a patient with a high viral load when breathing, speaking, and coughing.[111] However, the authors noted that this failure may be explained by the protective design of the patient isolation room.[111] In another case, virus was detected on the surface of a patient's bathroom exhaust air louvre, possibly due to toilet flushing, and in one corridor air sample, but not from four samples of the patient's exhaled air.[54] In this study, surface and air samples from room and rooftop ventilation equipment were also negative. As evidence against airborne transmission, two studies have cited the absence of infection of unmasked susceptible patients or healthcare workers although exposed to a coughing, initially unmasked COVID-19 patient with a high viral load[112] or when susceptible healthcare workers did not use contact or droplet precautions.[113]

While at present the evidence for airborne transmission may be considered incomplete and inconsistent, some have called for equivalent, direct confirmatory evidence that the assumed routes of droplet and fomite transmission are in fact the sole or primary exposure routes outside medical and similar settings.[114] These scientists have asked why a much higher level of evidence is required to demonstrate airborne transmission,[114] which can be reduced, even if not entirely prevented, with appropriate building engineering controls.[41] Given the evidence that persons in crowded and poorly ventilated spaces are at increased risk of exposure to respiratory aerosols,[5,21,69-71] proper ventilation and filtration to prevent or at least reduce airborne transmission should be considered for schools.

Ventilation rates in California schools

Heating, ventilating, and air-conditioning (HVAC) systems can affect airborne contaminant concentrations (and thus indoor exposures) in several ways, including the amount of "clean" *outdoor air* provided to occupied spaces (referred to as the ventilation rate, or VR) and the efficiency of any particle filters in the HVAC system. The more outdoor air that is brought into a building (i.e., the higher the VR), the more indoor air is exhausted from the building. This reduces the indoor concentration of contaminants that are produced indoors, including any small airborne virus-containing or bacterium-containing particles emitted by infected occupants when they breath, talk, cough, or sneeze, as well as air concentrations of any disinfectants or other chemicals used indoors or emitted from building products and furniture.

The VR in a classroom is related to the configuration of the building and ventilation system. California school classrooms include a wide variety of building and ventilation types. "Relocatable" classrooms are prefabricated buildings holding one or more classrooms, usually ventilated by "unit" ventilator systems in each room (approximately 30 percent of California's K-12 public school classrooms in 2004).[115] Other classrooms are in "site-built" (or "permanent") school buildings, which can have unit ventilator in each classroom or central ventilation systems for multiple classrooms and other parts of the buildings. Any of these mechanical systems may or may not include conditioning of the air (cooling as well as heating). Classrooms with no mechanical ventilation have "natural" ventilation only, through openable windows and doors. The type of classroom (relocatable vs. permanent) may affect the ventilation method and HVAC equipment commonly chosen. For example, a study of California schools with recently retrofitted HVAC equipment reported that relocatable classrooms predominately used wall-mounted HVAC systems, and permanent classrooms predominately used rooftop units.[116] Another study found that, compared to permanent classrooms, relocatables more often are equipped with packaged HVAC systems with heat pumps, and have wall air handling units, automatic supply fan operation, and windows that open.[115] A deeper understanding of these different features in each type of classroom is important for identifying the most effective and energy-efficient measures for increasing VR.

Particle filters in HVAC systems remove particles from the air supplied by the HVAC system, including both the "fresh" outdoor air and any air recirculated from indoors. The more efficient a filter, the higher the proportion of particles removed. For any filter, the proportion of particles removed varies by particle size, with both larger and smaller particles being the easiest to remove, and the hardest particles to remove being those with intermediate diameter of around 0.3. For example, a filter rated with a Minimum Efficiency Reporting Value (MERV) 14 or higher will on average remove 75 percent or more of particles in the 0.3–1.0 µm size range based on ASHRAE 52.2.[117] For a MERV 13 filter, which is the target minimum filtration level recommended in ASHRAE guidance for reopening schools[41] and the lowest MERV rating for which ASHRAE 52.2 reports removal efficiencies for particles of 0.3–1.0 µm, an average removal of ≥65 percent of 0.3–1.0 µm particles may reasonably be assumed. This assumes that the filter is properly installed and maintained, i.e., with no air bypassing the filter and regular filter replacement. In comparison, a MERV 8 filter is minimally effective at removing particles in the 0.3–1.0 µm size range. Thus, because both higher outdoor air VRs and more efficient filtration of recirculated air in buildings reduce the concentration of indoor-generated small airborne particles, each would lower any long-range transmission of SARS-CoV-2 indoors by these airborne particles. For classrooms without mechanical HVAC systems, i.e., those dependent entirely on openable windows and doors for ventilation, window fans may be used to increase the delivery of the outdoor air to the occupied space (but if used, should be configured not to increase air movement near the occupants). With natural ventilation, filtration is still possible if portable air cleaners are used within the room to remove particles in the air. Portable air cleaners can also be used in rooms with HVAC systems to further increase particle removal.

The California Building Standard Codes (Cal. Mechan. Code [CMC], Title 24, Part 4–, and Cal. Energy Code [CEC], Part 6) require all occupied buildings, including educational facilities, to have ventilation systems designed and installed that are capable of providing at least the code-specified minimum amount of outdoor air ventilation.[118] In addition, the California Education Code requires school districts to maintain schools in good repair, including providing HVAC systems that are functional, supplying an adequate (not specified) amount of air to all classrooms, and maintaining interior temperatures within acceptable ranges.[119] The California Code of Regulations (Title 8, §§ 5142-5143) also include ventilation provisions that apply to schools and other public workplaces; these provisions are applicable for the protection of workers only, not students.[120,121] The regulations require that HVAC systems be maintained and operated to provide at least the quantity of outdoor air required by the State Building Standards Code in effect at the time the building permit was issued. They also require that HVAC systems be operated continuously during working hours, with stated exceptions, and require the regular replacement or cleaning of filters to prevent significant reductions in airflow.

However, while the *types* of ventilation typically used in California schools are known, little is known about the actual *numbers* of each specific ventilation type in current California schools, due to the lack of any state-wide assessment of school facilities.[122] For the same reason, even less is known about the operation and conditions of these systems.[122] According to a recent nationwide survey, 41 percent of public school districts in six states, including California, needed updating or replacement of HVAC systems in at least half of their schools; HVAC systems were the leading building system or feature of concern.[122] Nationwide, inadequate school funding poses challenges for correcting these problems.

Currently, little to no information is available on how classroom VRs and filtration influence the risk of acquiring COVID-19 in schools generally, and how adequately the current VRs and filtration in California classrooms are protecting students from airborne transmission. However, several existing studies have documented that the ventilation in California classrooms is usually inadequate, with most classrooms not providing even the minimum 7 L/s-person VR specified in California building codes.[116,118,123,124] For air-conditioned California elementary school classrooms, 25 percent had VRs less than 2-L/s-person and 5 percent less than 1.4 L-s/person.[124] This study of VRs and illness absence in California elementary schools suggested that increasing classroom VRs above the State standard might not only substantially decrease illness absence (−1.6 percent for each additional 1 L/s-person of VR), but also could produce economic benefits far exceeding the cost of providing the increased ventilation. Specifically, the study estimated that increasing classroom VRs from their current low level to the State VR standard would decrease illness absence by 3.4 percent and would increase attendance-linked State funding by $33 million annually, while increasing energy costs by only $4 million.[124] Despite these and related findings on low VRS in schools, efforts to increase VRs in California classrooms have had limited success.[125] The new challenge of reducing SARS-CoV-2 transmission in schools may bring increased attention to this important ongoing problem and new motivation to improve ventilation and filtration in schools. Improvements in these systems would also reduce all indoor particle concentrations and improve indoor air quality in classrooms in general.

Model description and input parameters

This paper introduces a model to provide rough initial estimates of the relationships of classroom VRs and filtration to the component of occupant infection probability due to assumed long-range airborne transmission of small aerosols. Our objectives are to illustrate the importance of providing adequate ventilation and filtration (in addition to social distancing, wearing masks, and intensified cleaning and disinfection) for safe school operation when reopening during the ongoing COVID-19 pandemic and to provide initial guidance for making decisions about these systems. In order to estimate the relative risks[126] of airborne transmission for classroom with different conditions, we constructed a simple interactive model in a spreadsheet. The model estimates the probability of infection (Appendix 3), based on a commonly used equation and the best available knowledge about the characteristics of California classrooms and of respiratory particles containing SARS-CoV-2. We then compared the relative rather than absolute risks for different scenarios, as this reduces the uncertainty related to specific assumptions about the rate of infectious respiratory emissions from infected persons[127] and focuses on the relative reductions in infection risk from the various ventilation and air filtration scenarios. It should be noted that this model is not meant to address the *overall* probability of infection because it does not account for very close-range transmission by infectious particles (whether large droplets or small aerosols), nor for transmission through fomites. These other two transmission modes should *not* be influenced by ventilation and filtration. Further limitations are discussed at the end of this section.

Wells-Riley equation and modification

One widely used method for modeling the risk of airborne transmission in enclosed environments is the Wells–Riley equation.[128] The model (Equation 1) is based on the concept of a "quantum of infection," whereby the rate of generation of infectious airborne particles (or *quanta*) is used to model the likelihood of a susceptible individual in a steady state, well-mixed, indoor environment being exposed to infectious particles and subsequently succumbing to infection.[129]

$$P_{infection} = \frac{N_c}{N_S} = 1 - e^{-\frac{Iqpt}{Q}} \quad (1)$$

where
$P_{infection}$ = the probability of infection
N_C = number of infected cases
N_S = number of susceptible individuals
I = number of infectious individuals
p = pulmonary ventilation rate of a person (m^3/h)
q = quanta generation rate produced by one infector (quanta/h)
t = exposure time (h)
Q = outdoor air ventilation rate (assuming clean outdoor air) (m^3/h).

Equation 1 only accounts for the role of outdoor air ventilation (Q). However, the reduced indoor concentration of airborne particles by HVAC filters and portable air cleaners may be considered as additional "equivalent" ventilation. To account explicitly for the potential risk reduction by filtration, we adopted a modified form of the Wells–Riley equation similar to Stephens[129] (Equation 2).

$$P_{infection} = \frac{N_c}{N_S} = 1 - exp\left[\frac{-Iqpt}{V(\lambda_{ventilation} + \lambda_{infiltration} + k_{filtration} + k_{deposition})}\right] \quad (2)$$

where
V = room volume (m^3)
$\lambda_{ventilation}$ = outdoor air change rate (i.e., infectious particle removal rate due to ventilation, assuming clean outdoor air (Q/V, h^{-1})
$\lambda_{infiltration}$ = air infiltration rate, i.e., infectious particle removal rate due to infiltration from the building envelope, assuming clean outdoor air (h^{-1})
$k_{filtration}$ = infectious particle removal rate due to filtration, i.e., HVAC filter or portable air cleaner (h^{-1})
$k_{deposition}$ = infectious particle removal rate due to deposition on surfaces (h^{-1}).

For a filter installed in a central HVAC system, the filtration removal rate ($k_{filtration}$) depends on the rate of airflow through the HVAC filter (Q_{filter}), the system operational time fraction (f_{HVAC}), and the removal efficiency of the filter (η_{filter}) (Equation 3a).

$$k_{filtration} = f_{HVAC} \frac{Q_{filter}\eta_{filter}}{V} \quad \text{(3a–for HVAC filter)}$$

where
f_{HVAC} = fractional HVAC operation time (%)
Q_{filter} = airflow rate through filter (m^3/h)
η_{filter} = removal efficiency of HVAC filter for infectious particles (%).

If a portable (in-room) cleaner with a High-Efficiency Particle Air (HEPA) filter is used, an equivalent filtration removal rate can be calculated from the Clean Air Delivery Rate (CADR) of the air cleaner[130] (Equation 3b).

$$k_{filtration} = \frac{CADR}{V} \quad \text{(3b–for portable air cleaner)}$$

where
CADR = clean air delivery rate of a portable air cleaner for infectious particles (m^3/h).

Both the removal efficiency of an HVAC filter (η_{filter}) and the CADR of a portable air cleaner are particle-size dependent. Estimation of these parameters requires detailed knowledge of the device's removal efficiency for indoor particles in general as well as the size distribution of virus-containing particles.

In addition to remaining airborne, infectious particles may also deposit onto and re-suspend from indoor surfaces. Particle deposition and resuspension are dynamic processes that may be influenced by many factors, such as particle size and density, room characteristics, surface characteristics and areas, and human activity level. As an initial, "zero-order," estimation, we used the measured particle deposition loss rate data for residences that are summarized by Dillon et al.[131]

Model implementation

We implemented the model described above in interactive spreadsheets, including one simplified version with reduced user inputs, one sheet with default values for additional hidden parameters, and a supplementary sheet with a simplified MERV table (Appendix 3). The sheet with simplified user inputs requires information for basic parameters (e.g., floor area, number of occupants, and time spent in room, and simplified choices of VR, MERV rating of HVAC filter, and CADR of portable air cleaner), thus is usable by anyone with general knowledge about a school classroom. The default values in the second spreadsheet can also be modified if users have more detailed knowledge of building operations and airborne transmission, including occupant breathing rate for different age groups and activity levels, quanta generation rate and size distribution of infectious particles, fractional operation time of the HVAC system, total supply airflow rate and the outdoor air fraction, and user-defined filter removal efficiency. Another sheet contains default removal efficiencies of MERV-rated filters that are automatically linked to the filter MERV rating a user enters in the simplified version. Additionally, we included a spreadsheet for a reference case (defined in the following section "Analysis and results of classroom scenarios") so that the RRs of infection for other ventilation and filtration conditions can be calculated. Again, although the model estimates absolute risk of infection for specific classroom conditions, we focused on the RRs from comparing different conditions, because the current uncertainty about inputs such as rate of quanta generation makes estimates of absolute infection risk very uncertain.

Determination of default model input parameters

- Room height (*H*)
  We used a ceiling height of 3.0 m, which is typical for a classroom, as a default.

- Pulmonary ventilation rate (*p*)
  Table 1 shows the range of eight-hour breathing rate estimates from the California Office of Environmental Health Hazard Assessment.[132] [132] We used a value of 0.5 m^3/h (or 4.0 m^3/8-h, the average of the mean 8-h breathing rates for 2 to <16 years of age for sedentary & passive and light intensity activities) as a default.

Table 1. Eight-hour breathing rate (m^3/8-h) point estimates for males and females combined[132]

	0 to <2 years	2 to <9 years	2 to <16 years	16 to <30 years	16–70 years
Sedentary & Passive Activities[a] (MET< 1.5) Mean	1.86	2.24	***2.37***	2.33	2.53
95th Percentile	2.69	2.99	3.20	3.23	3.34
Light Intensity Activities[b] (1.5 < METs ≤ 3.0) Mean	4.61	5.44	***5.66***	5.72	6.03
95th Percentile	6.51	7.10	7.52	7.75	7.80
Moderate Intensity Activities[c] (3.0 < METs ≤ 6.0) Mean	8.50	10.20	10.84	12.52	12.94
95th Percentile	12.36	13.47	14.52	18.08	18.07

[a] Resting
[b] Activities within a classroom
[c] Activities during recess and some physical education classes

- Quanta generation rate (*q*)
  Very limited data are available for SARS-CoV-2 and the estimates vary widely. Buonanno et al. identified three emission rates: (i) low, <1 quantum/h; (ii)

intermediate, ≤100 quanta/h;[133] and high, >100 quanta/h.[134] A study of healthcare workers attending COVI-19 patients estimated a transmission rate of 0.225 quanta/h.[135] Another analysis using data from two outbreaks estimated four emission rates of 0.36, 2.4, 4.9, and 31 quanta/h for oral breathing at rest, oral breathing during heavy activity, speaking during light activity, and singing or speaking loudly during light activity, respectively.[136] Dai and Zhao estimated a generation rate of 14–48 quanta/h.[137] Miller et al. modeled a super spreader outbreak among a rehearsing choral group and estimated a mean quanta emission rate of 970.[138] Quanta generation rate varies with the type of vocalization, being higher for singing and coughing than for speaking.[139] Here, we assumed that individuals with persistent cough would not be present in the classroom and thus used a value representative of speaking (i.e., 1 quantum/h). Appendix 2 provides a more complete summary of quanta generation rates for common aerosol transmissible diseases.

WHO and CDC have recognized the role of mask use as a source control measure and its effect in preventing transmission from infected individuals to others. We considered a reduction of the quanta generation rate in the model to account for the effect of cloth mask wearing, using an assumed reduction of 50 percent.[140] We also conservatively assumed 0 percent inhalation protection provided by cloth mask wearing.

- Fractional operation time of HVAC system (f_{HVAC})
  We used 100 percent as a default, assuming that the HVAC system operates and provides ventilation and filtration continuously while the room is occupied.

- Outdoor air ventilation rate ($\lambda_{ventilation}$)
  Title 24—in both Part 4 (CMC) and Part 6 (CEC)—requires that buildings with no mechanical supply of outdoor air have windows with a total openable area of at least 4 percent of the floor area.[118] While Title 24 permits openable windows for outdoor air ventilation as an alternative to a mechanical supply of outdoor air, openable windows do not ensure that adequate outdoor air is provided to the space, as the amount of outdoor air entering through windows depends on the outdoor wind speed and the indoor-outdoor temperature difference. In addition, windows are often closed when the outdoor temperature is too cold or hot or the level of outdoor noise is too great, precluding any outdoor air from entering through the windows.

  As an alternative to openable windows, both the CMC and CEC require a mechanical supply of outdoor air. Both list code-required mechanical outdoor air VRs for a total of 14 educational facility space types, including classrooms, science laboratories, art classrooms, wood/metal shops, and music/theater/dance rooms. However, the code-required mechanical outdoor air VRs per the CMC and CEC differ. The CEC-required outdoor air VRs are greater than the CMC requirements for 8 of 14 educational spaces, with 5 of them having a ventilation requirement that is equal or greater by 10 percent.

The interactive spreadsheet allows the user simply to enter a VR per person (in units of L/s-person) or per floor area (in units of L/s-m^2) that is either calculated based on the above code requirements or obtained from actual measurements. We provide five example calculations in the following section "Analysis and results of classroom scenarios."

This model is for classrooms with a mechanical supply of outdoor air and cannot be used for classrooms with no mechanical supply of outdoor air but only openable windows, as the VRs in these classrooms are highly variable depending on local weather conditions.

- Air infiltration rate ($\lambda_{infiltration}$)
  Infiltration refers to air leakage through unintentional openings in the exterior envelope of a building, driven by wind, indoor-outdoor temperature difference and equipment operation.[141] Little to no data are available for the air infiltration rates in classrooms with no mechanical ventilation and all windows closed. Here we assumed an infiltration rate of 0.2 ACH, which is close to the median infiltration rate reported for occupied homes with no mechanical ventilation and windows closed in a California new home study.[142] We also assumed that the mechanical systems are "balanced," and that this small amount of infiltration is simply additive to the mechanical-ventilated outdoor air.

- Airflow rate through a filter (Q_{filter})
  Equation 2 assumes that the air entering the filter is the recirculated air, with the average indoor concentration of infectious particles. Depending on the ventilation system type as well as the thermal load of the classroom, the total supply airflow rate, and the fraction of recirculated air in the supply air may vary. We assumed a constant air volume system with a total supply airflow rate equivalent to 6 ACH (i.e., 5.0 L/s-m^2 or 16.5 L/s-person for the hypothetical classroom defined in this paper) as a default. The recirculated airflow rate was then calculated as the difference between the total supply air and outdoor airflow rates.

- Removal efficiency of a HVAC filter for infectious particles (η_{filter})
  Commercial HVAC filters often have a MERV rating. These MERV ratings are established based on size-resolved removal efficiencies for 0.3–10 μm particles measured in a laboratory setting according to ASHRAE Standard 52.2.[117] A table of filter MERV ratings and associated removal efficiencies is available in ASHRAE Standard 52.2 (Appendix Table J-2). However, it does not report removal efficiencies for the particle size ranges of 0.3–1 μm and 1–3 μm for low MERV-rated filters. Meanwhile, Dillon and Sextro summarized the single-pass filtration efficiency distributions for 0.1–μm, 0.3–μm, 1–μm, 3 μm, and 10–μm particles for a range of filters (i.e., MERV 0, 5, 7–8, 11–12, and 14–15), considering efficiency variation both (a) within similarly rated filters and (b) due to filter loading over the filter lifetime.[143]

Table 2 summarizes the removal efficiencies of MERV-rated filters that we assumed for particles in three size ranges—0.3–1, 1–3, and 3–10 µm. To be conservative, we used the lower bound of the minimum composite average particle size removal efficiencies specified in ASHRAE 52.2 Table J-2 (i.e., apply to MERV 14–16 filters for 0.3–1 µm particles, MERV 10–16 filters for 1–3 µm particles, and MERV 5–16 filters for 3–10 µm particles). We also assumed a filtration efficiency of 65 percent for MERV 13 for 0.3–1 µm particles, 40 percent for MERV 9 for 1–3 µm particles, and 10 percent for MERV 1–4 filters for 3–10 µm particles. For low MERV-rating filters that do not have removal efficiencies specified in ASHRAE 52.2 Table J-2 (i.e., MERV 1–12 filters for 0.3–1 µm particles, and MERV 1–8 filters for 1–3 µm particles), we used the 50th percentile of the cumulative filtration efficiency distributions ($P_{50\%}$) from Dillon and Sextro.[143] For filters of MERV 1–12, we used the average of $P_{50\%}$ for 0.3 and 1 µm for particles in the size range of 0.3–1 µm. For filters of MERV 1–8, we used the average of $P_{50\%}$ for 1 and 3 µm for particles of 1–3 µm. If $P_{50\%}$ was not given for a specific MERV rating filter (i.e., MERV 1–4, 6, 9 and 10), we used the value for the closest lower MERV-rating filter. To make a conservative estimate, we further divided these $P_{50\%}$ values by a factor of three.

Table 2. Assumed removal efficiencies of various MERV filters for particles in three size ranges

HVAC filter MERV rating	Assumed removal efficiency (%) 0.3–1.0 µm	Assumed removal efficiency (%) 1.0–3.0 µm	Assumed removal efficiency (%) 3.0–10.0 µm
1	0	0	10
2	0	0	10
3	0	0	10
4	0	0	10
5	2	8	20
6	2	8	35
7	15	28	50
8	15	28	70
9	15	40	85
10	15	50	85
11	19	65	85
12	19	80	90
13	65	90	90
14	75	90	90
15	85	90	90
16	95	95	95

As for the size distribution of virus-containing particles in room air, very limited data are available for SARS-CoV-2. Stephens, largely based on work with influenza A from Lindsley et al.,[144] assumed a particle size distribution of infectious particles: 15 percent, 25 percent, and 60 percent in 0.3–1, 1–3, and 3–10 µm size ranges, respectively. Based on recent air sampling results for SARS-CoV-2,[53,58] we assumed the following slightly different proportions:

- 20 percent of infectious particles in the 0.3–1 µm size range
- 30 percent in the 1–3 µm size range
- 50 percent in the 3–10 µm size range.

The viral load in respiratory secretions, e.g., sputum, saliva, and fluid accumulated in the lungs because of pneumonia, likely varies at different stages of infection. However, knowledge of viral load is not needed when the fractional distribution of respiratory particles can be estimated, assuming the virus is distributed uniformly throughout respiratory secretions and, therefore, throughout exhaled particles.

The spreadsheet calculates a size-weighted average filtration efficiency for infectious particles based on the MERV rating of the filter that a user enters.

- Clean Air Delivery Rate (CADR) of portable air cleaners for infectious particles
  The CADR of a portable air cleaner indicates the volume of filtered air directly delivered to the room. A portable air cleaner, as certified by the Association of Home Appliance Manufacturers (AHAM), often lists three CADR numbers—one for tobacco smoke (0.09–1.0 µm), one for dust (0.5–3 µm), and one for pollen (5–11 µm).[145] With the very limited available data for the size distribution of SARS-CoV-2 containing particles in room air, we simply assumed the following and directly utilized the CADR numbers for tobacco smoke, dust, and pollen when estimating the effect of using a portable air cleaner:
  - 20 percent of infectious particles in the 0.09–1.0 µm tobacco smoke size range
  - 30 percent in the 0.5–3 µm dust size range
  - 50 percent in the 5–11 µm pollen size range.

  The spreadsheet assumes that the portable air cleaner operates continuously and calculates a size-weighted average filtration efficiency for infectious particles based on the CADR numbers for the three size fractions that a user enters.

- Infectious particle removal rate due to surface deposition ($k_{deposition}$)
  We assumed the same particle size bins used for HVAC filter MERV ratings for simplicity. We used the 50th percentile of the cumulative frequency distributions of particle deposition loss rates ($P_{50\%}$) from Dillon et al.[131] For particles in the size range of 0.3–1 µm, we used the average of $P_{50\%}$ for 0.3 and 1 µm. For particles of 1–3 µm, we used the average of $P_{50\%}$ for 1 and 3 µm. For particles of 3–10 µm, we used the average of $P_{50\%}$ for 3 and 10 µm. To make a conservative estimate, we further divided them by a factor of three. The $k_{deposition}$ determined was 0.14, 0.29 and 0.91 h^{-1} for infectious particles in the size range of 0.3–1, 1–3, and 3–10 µm, respectively, which led to a size-weighted removal rate of 0.57

h^{-1} with the assumed size distribution (i.e., 20 percent, 30 percent, and 50 percent for infectious particles of 0.3–1, 1–3, and 3–10 µm, respectively).

Model limitations

It is important to note the following limitations to be aware of when using the model:

- The model assumes that the indoor air has reached steady state with continuous room occupation and is well-mixed (i.e., infectious airborne particles are evenly distributed in the occupied space).
- The model assumes the same default quanta generation rate for all infected persons and a default pulmonary ventilation rate of 0.5 m^3/h for all occupants. Actual values may differ due to differences in activity level and the effect of age on COVID-19 transmission and susceptibility.
- The model does not consider additional limiting factors that may be common in practical applications. For instance, filter bypass can result from improper filter fitting, design, or installation within HVAC units. Filter ratings also are based on ideal modeled conditions and not necessarily real-world conditions. These factors all can reduce the actual benefits of filtration.
- Outdoor and filtration airflow rates may be less than expected due to deferred HVAC maintenance or incorrect operation, resulting in problems such as closed outdoor air dampers, obstructed outdoor air inlet screens, dirty filters that are past their service life and are restricting airflow , fan controls not set for continuous operation during classroom hours (e.g., thermostat fan switches set for “auto” or “off” and not for “on”), improperly set HVAC start/stop time clocks, or out-of-calibration carbon dioxide (CO_2) sensors for demand-control ventilation (DCV) systems.
- The default model input parameters were based on current information about the possibility of airborne transmission of SARS-CoV-2. However, knowledge of the dominant transmission routes, quanta generation rates, and the size-distribution of infectious particles is rapidly evolving.

Analysis and results of classroom scenarios

Defining the reference case

We defined a hypothetical classroom environment (see Table 3 for basic user input parameters), and a reference case that operates at the code-required minimum VR and uses a MERV 8 filter. We used the larger of the Title 24 CMC and CEC code-required minimum outdoor air VRs for classrooms (age ≥9 years): the CEC code requirement for the greater of 7 L/s-person or 1.93 L/s-m^2.[118] Thus, for the modeled 89.7-m^2 classroom with 27 occupants, this code-required minimum VR is 7 L/s-occupant.

Table 3. Basic input parameters used for a hypothetical classroom environment

Parameter	User input value	Units
Room floor area[a]	89.3	m^2
Room occupancy[a]	27	person
Exposure time[b]	5	h
Number of infected individuals	1	person
Total number of non-susceptible occupants, e.g., current infection or immune (previous recovery or vaccination)	1	person

[a] The floor area and occupancy of a school classroom defined in a *Standard Method for the Testing and Evaluation of Volatile Organic Chemical Emissions from Indoor Sources Using Environment Chambers* were used.[146] It was based on the dimensions of a typical relocatable classroom.

[b] Assume a total school time of 7 h (i.e., 8 a.m.–3 p.m.) with approximately 70 percent of the time in a classroom.

A focus on relative risk (RR)

There are wide ranges and large uncertainties of quanta generation rates reported in the literature, so we first conducted a sensitivity analysis to better understand the impact of this parameter on the modeling results. Because we assumed only asymptomatic infected individuals, we considered a quanta generation range of 0.1–100 quanta/h. Results (Figure 2) indicate that for the exposure scenarios considered, the predicted probability of infection increases nearly linearly with an increase in quanta generation rate. In Figure 2, we also plotted "inhaled quanta" as the second x-axis, which is the combination of all the variables in the exponential term ($Iqpt/Q$) in Equations (1) and (2). Although the probability of infection would gradually increase non-linearly and eventually begin to plateau (i.e., approach 100 percent) with the increase of "inhaled quanta," the "inhaled quanta" for the classroom scenarios we modeled in this paper are predominantly in the lower range (i.e., < 0.2), in which the probability of infection increases approximately linearly with the increase in "inhaled quanta."

The quanta-generation rate of SARS-CoV-2 from infected individuals has still not been determined and estimates have varied widely given the outbreaks that have been studied (Appendix 2). To reduce the importance of the specific default quanta generation rate used in the models (1 quantum/h) on the interpretation of modeling results, we report the *relative risks*[126] of infection for various ventilation and filtration conditions, compared to the reference case.

Besides the quanta generation rate, the assumed infectious particle size distribution in indoor air is also a key model parameter that strongly influences the absolute risk of infection but has large uncertainty. However, Azimi and Stephens have modeled a hypothetical office environment and have demonstrated that this uncertainty could be largely cancelled out in RR estimates.[127] They showed that, in modeling infection risk from aerosols, changing assumed values for infectious particle size distribution or quantum-emission rate greatly influenced absolute risks but had small effects on RRs.

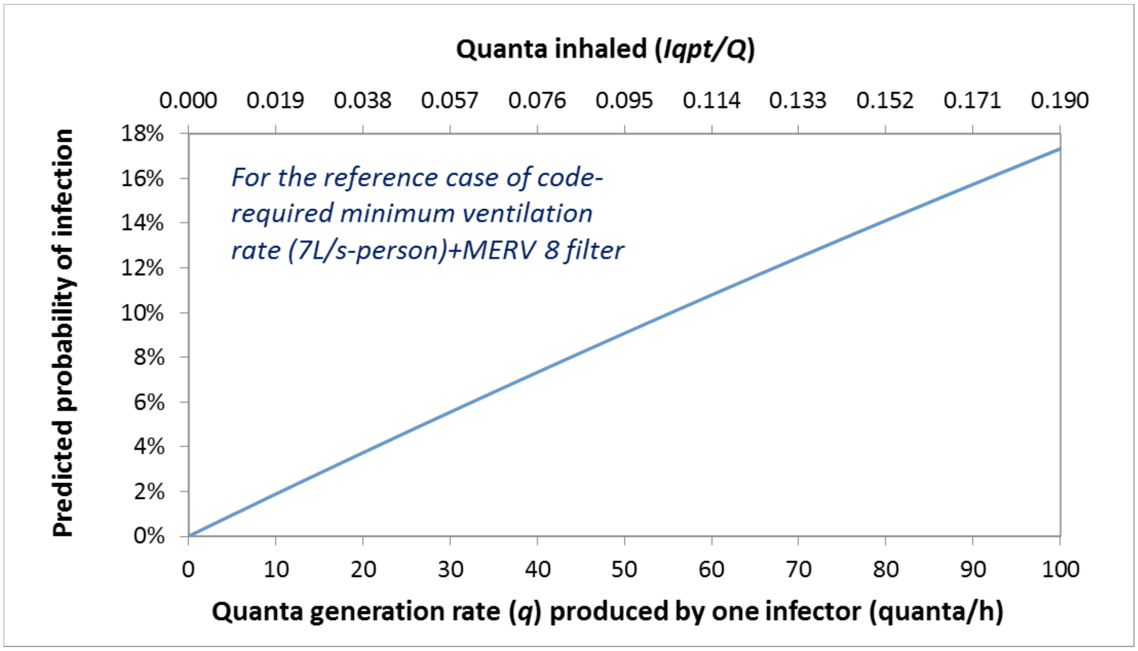


Figure 2. Risk of SARS-CoV-2 infection in a hypothetical classroom, based on input parameters defined in Table 3 and other default values defined in this paper for a reference case (code-required minimum ventilation rate (VR = 7 L/s-person) and a MERV 8 filter).

Risk reduction from intervention strategies

We analyzed four series of scenarios as initial estimates of the potential effects of ventilation, additional filtration, additional portable air cleaner use, and mask-requirement policies in reducing SARS-CoV-2 transmission indoors (Table 4).

Table 4. Classroom scenario analysis for different ventilation, filtration, and mask-wearing conditions. Scenario 1: Poor ventilation (current median for air-conditioned classrooms, 2.8 L/s-person,[124] 40% of Title 24 code requirement). Scenario 2: Somewhat under-ventilated (current median for classrooms with recently retrofitted HVAC equipment, 4.8 L/s-person,[116] approximately 70% of Title 24 code requirement). Scenario 3: Meets Title 24 code requirement of 7 L/s-person. Scenario 4: Well above Title 24 minimum code requirement, 10.5 L/s-person, 150% of Title 24 code requirement

Scenario case number	Enhanced filtration: Upgrade to MERV 13 filter	Enhanced filtration: With additional portable air cleaner(s)[a]	Teacher & students wear masks[b]	Relative risk of infection, compared to reference case[c]
1a	No	No	No	120%
1b	No	No	**Yes**	60%
1c	**Yes**	No	No	82%
1d	**Yes**	No	**Yes**	41%
1e	No	**Yes**	No	60%
1f	No	**Yes**	**Yes**	30%
2a	No	No	No	110%
2b	No	No	**Yes**	55%
2c	**Yes**	No	No	80%
2d	**Yes**	No	**Yes**	40%
2e	No	**Yes**	No	58%
2f	No	**Yes**	**Yes**	29%
3a[c]	***No***	***No***	***No***	***100%***
3b	No	No	**Yes**	50%
3c	**Yes**	No	No	79%
3d	**Yes**	No	**Yes**	39%
3e	No	**Yes**	No	55%
3f	No	**Yes**	**Yes**	27%
4a	No	No	No	88%
4b	No	No	**Yes**	44%
4c	**Yes**	No	No	76%
4d	**Yes**	No	**Yes**	38%
4e	No	**Yes**	No	51%
4f	No	**Yes**	**Yes**	25%

[a] AHAM recommends choosing a portable air cleaner with a tobacco smoke CADR (in units of ft^3/min or CFM) at least 2/3 of the room area (in units of ft^2). The suggested CADR for the classroom defined in Table 3 is 1087 m^3/h (or 640 ft^3/min), which was used in the scenario analysis.

[b] A 50% reduction in quanta generation rate was assumed if teacher and students wear masks.

[c] Case 3a is the reference (i.e., with code-required minimum VR and a MERV 8 filter).

In addition to the code-required minimum VR scenario, we also modeled three other VR scenarios (two with less and one with more than the code VR). In scenario 1, 2.8 L/s-person is the median VR reported in Mendell et al. for California classrooms with AC units (based on 3rd–5th grade classrooms in three California school districts)[124] and 40 percent of the Title 24, Part 6, CEC code-required minimum. In scenario 2, 4.8 L/s-person is the median VR from Chan et al. for California classrooms with recently retrofitted HVAC equipment[116] and approximately 70 percent of the code-required minimum. In scenario 3, 7 L/s-person is the current code-required minimum;[118] and in scenario 4, 10.5 L/s-person is 150 percent of the code-required minimum. Each ventilation scenario uses a MERV 8 filter (a) as a baseline filtration level.

For enhanced HVAC filtration, MERV 13 filters were used (c and d); these offer both reasonable removal efficiency for the hardest to remove particle sizes, as well as practicality in terms of cost and pressure drop. Use of MERV 13 or better filters where possible also is recommended in ASHRAE's school reopening guidance.[41,147] For enhanced particle filtration, a CADR of 1087 m^3/h (or 640 ft^3/min) was assumed if using portable air cleaner(s) (e and f). This CADR number is based on the floor area of the hypothetical classroom and AHAM's 2/3 Rule for choosing a portable air cleaner. For the model calculations in this paper, we have assumed a CADR of 1087 m^3/h for each of the particle size test ranges: tobacco smoke (0.09–1.0 µm), dust (0.5–3 µm), and pollen (5–11 µm). We note that having the same CADR for all three particle size ranges is only applicable to portable air cleaners with HEPA filters. For air cleaners with less efficient, non-HEPA filters, the CADR will not be the same for the three particle size ranges (smoke is less than dust removal, and dust is less than pollen removal) and the specific CADRs can be input into the model. These assumed values are mainly for illustration purposes.

Figure 3 shows the results of analyses under the specific assumptions and conditions defined for this hypothetical classroom, which are also reported in the "Relative risk of infection" column in Table 4. A poorly ventilated classroom (1a) could increase the relative probability of infection by 20 percent compared to a classroom with ventilation that meets the minimum code requirement (3a). Wearing a mask (with an assumed 50 percent reduction in quanta generation rate) could lower the relative probability by approximately half for each ventilation scenario (b vs. a). With the additional upgrade of the HVAC filter from MERV 8 to MERV 13 (4d, 3d, 2d and 1d), the relative probability of infection from long-range, small particles could reduce to 38–41 percent of that for the reference case. With the use of portable air cleaners (with AHAM-recommended CADR) in addition to mechanical ventilation with MERV 8 filter (4f, 3f, 2f and 1f), the relative infection probability could reduce to 25–30 percent of that for the reference case. It should be noted that more than one portable air cleaner may be needed to reach the desired CADR, following AHAM's 2/3 rule,[130] because most commercially available portable air cleaners have CADRs in the range of 170–680 m^3/h (100–400 ft^3/min).

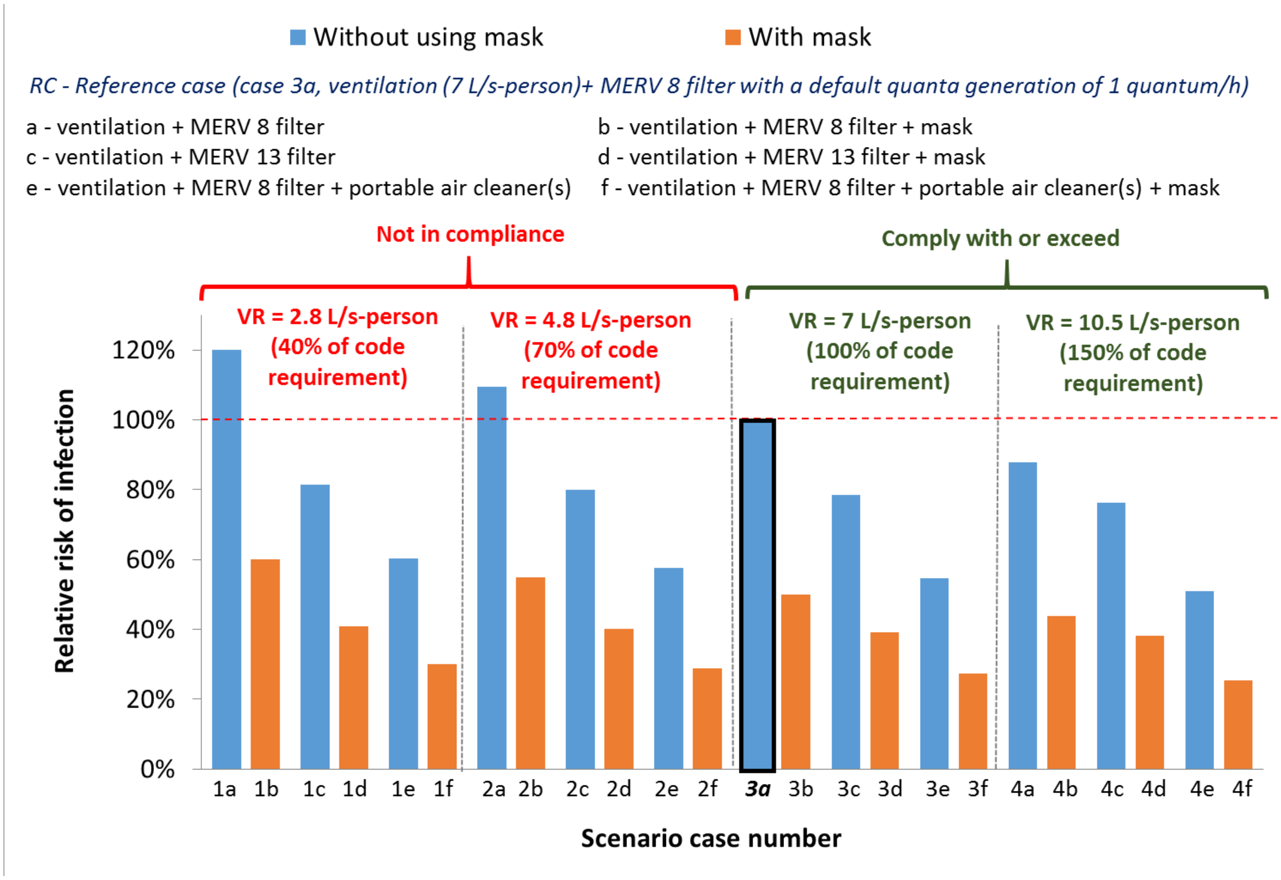


Figure 3. Relative risks of SARS-CoV-2 infection in a hypothetical classroom, compared to the reference case (3a), based on input parameters defined in Tables 3 and 4 and other default values defined in this paper for four ventilation rates: two below (scenarios 1 and 2) and two in compliance with (scenarios 3 and 4) California Title 24 ventilation requirements.

Under current model assumptions, mask use is equally or more effective than either of the enhanced filtration strategies in isolation for all modeled ventilation scenarios. It must be noted that this comparison does not consider close-range transmission between occupants, for which masks are the best preventive strategy and HVAC systems will provide little exposure reduction.

A scenario with no classroom ventilation

In addition to the above four ventilation scenarios, we also modeled an extreme "no ventilation" scenario which may occur under the following situations:

- Classrooms have no mechanical ventilation, just openable windows, and the windows are closed (e.g., due to rain, uncomfortable outdoor temperature, outdoor noise, or wildfire smoke).
- Classrooms have a mechanical ventilation system, but the system is unintentionally off because of operation clock error or fan controls are set for

"auto" and not "on," thus operating only when heating or cooling is needed; or intentionally off, such as when a teacher turns off a noisy system in a relocatable classroom so that students can hear better.
- Classrooms have a mechanical ventilation system operating, but the outdoor air damper is unintentionally closed due to damper control failure, or intentionally closed to exclude wildfire smoke.

For this scenario, we considered only 0.2 ACH air infiltration and modeled eight hypothetical cases (E-I to E-VIII) to demonstrate the impact of mask wearing and different filtration strategies (MERV 8 filter, MERV 13 filter, or AHAM-sized portable air cleaner) under this situation. We included the cases of using MERV 8 (E-III and E-IV) and MERV 13 filters (E-V and E-VI) because classrooms with a mechanical HVAC system operating, even if the outdoor air damper is closed, will still benefit from an HVAC filter that removes infectious particles from recirculated air. For these cases (E-III to E-VI), we assumed a total supply airflow rate equivalent to 6 ACH (same as specified before) and 100 percent recirculated air.

Figure 4 shows the results of this analysis. Under the specific assumptions and conditions defined for the no ventilation/air cleaning scenario (E1), the RR of infection from long-range, small aerosols could increase to more than six times as high as that for the reference case (E-I vs. 3a). Wearing a mask (with an assumed 50 percent reduction in quanta generation rate) could lower the RR of infection by approximately half (E-II vs. E-I). In combination with mask-wearing, use of a MERV 8 or MERV 13 filter (i.e., in a classroom where the HVAC system operates continuously with 100 percent recirculated air) or AHAM-sized portable air cleaner(s) (i.e., in classroom with closed windows and no or a non-operating mechanical ventilation system) could further reduce the RR of infection (i.e., compared to the reference case) to 69 percent (E-IV), 42 percent (E-VI), and 51 percent (E-VIII), respectively. In our model, results show a significant reduction of infection probability even for the use of a MERV 8 filter, because we assumed only 20 percent of infectious particles are in the 0.3–1 μm size range. These results may change with evolving knowledge on the size distribution of virus-containing particles.

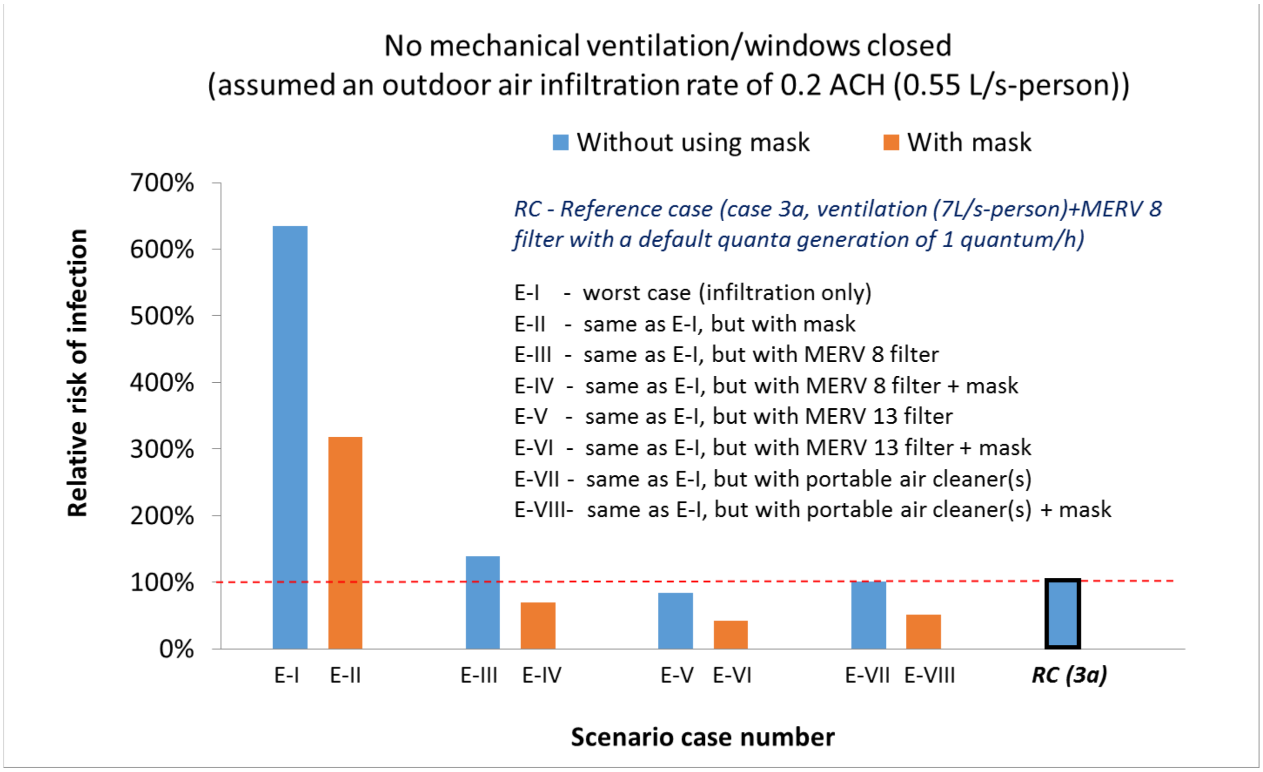
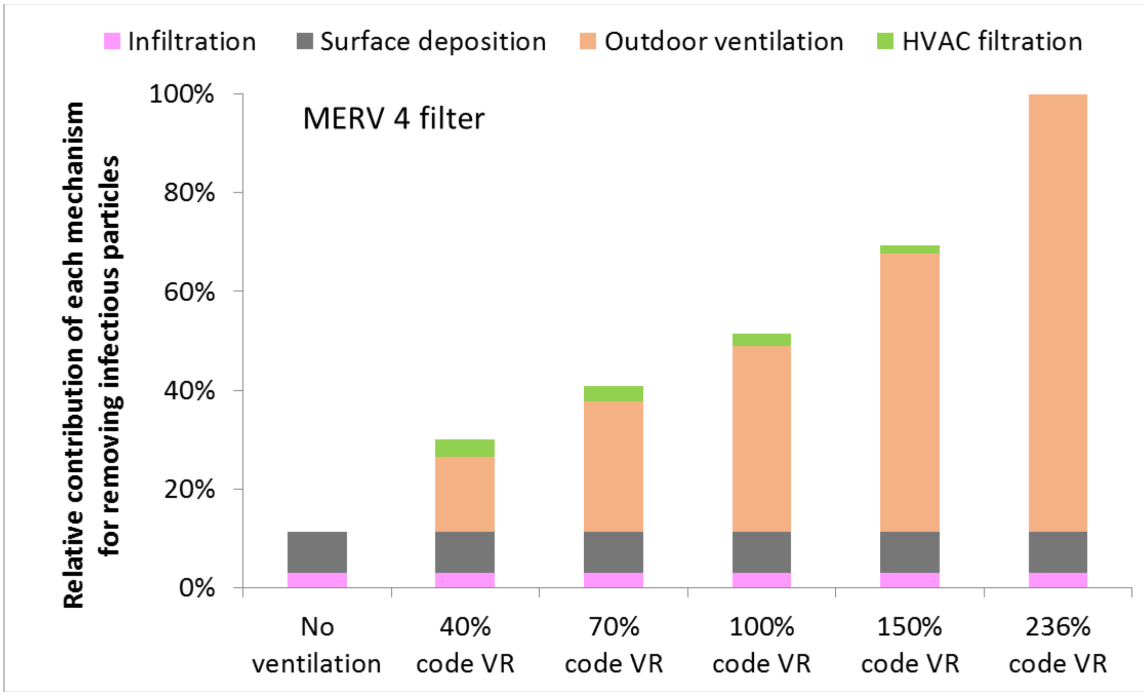


Figure 4. Relative risk of SARS-CoV-2 infection in a hypothetical classroom with “no ventilation,” compared to a reference case (RC 3a) and based on input parameters in Tables 3 and 4 and other default values defined in this paper: no filtration (E-I and E-II), MERV 8 filter (E-III and E-IV), MERV 13 filter (E-V and E-VI), and one or more portable air cleaners with a total of 1087 m^3/h CADR (E-VII and E-VIII).

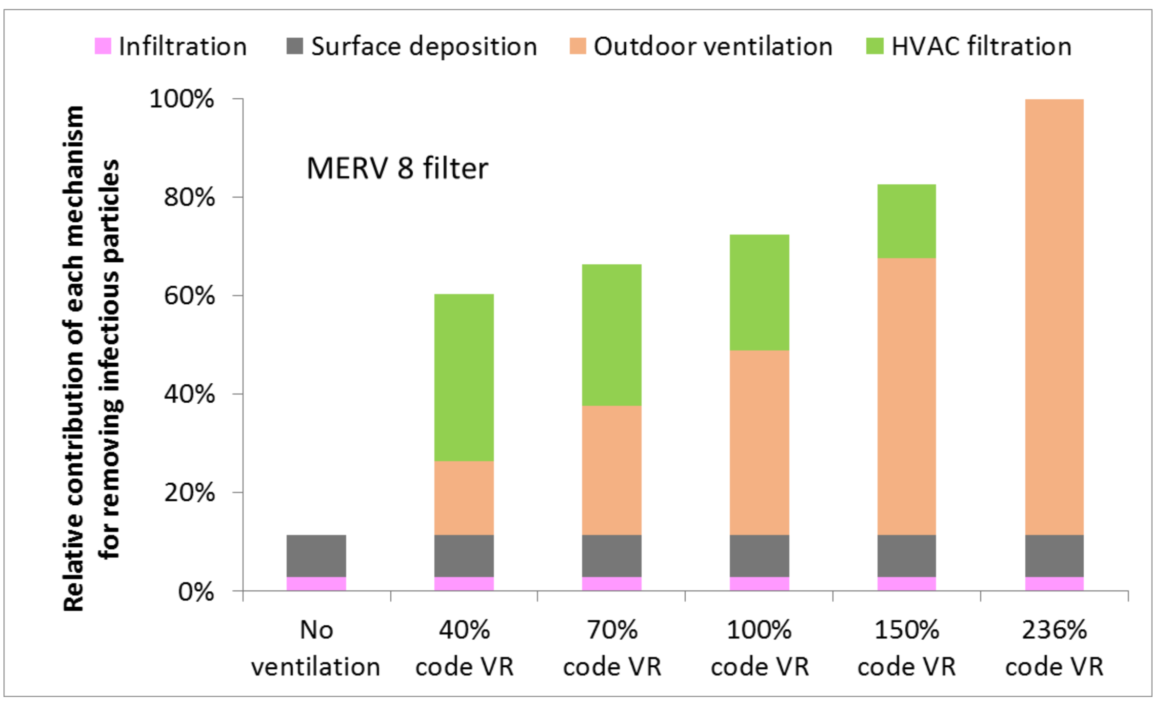
Contribution of each mechanism to total infectious particle removal

Figures 5a to 5c show the relative contributions of each mechanism for removing SARS-CoV-2 virus-containing particles with increased levels of HVAC filtration (i.e., MERV 4 vs. MERV 8 and MERV 13) under various VRs. We included a MERV 4 filter in the comparison because some classrooms may have a filter less efficient even than MERV 8 (the default filtration level in the reference case). We defined the maximum possible infectious particle removal rate as 100 percent, achievable by the provision of 236 percent of the code-required VR (i.e., 100 percent outdoor air).



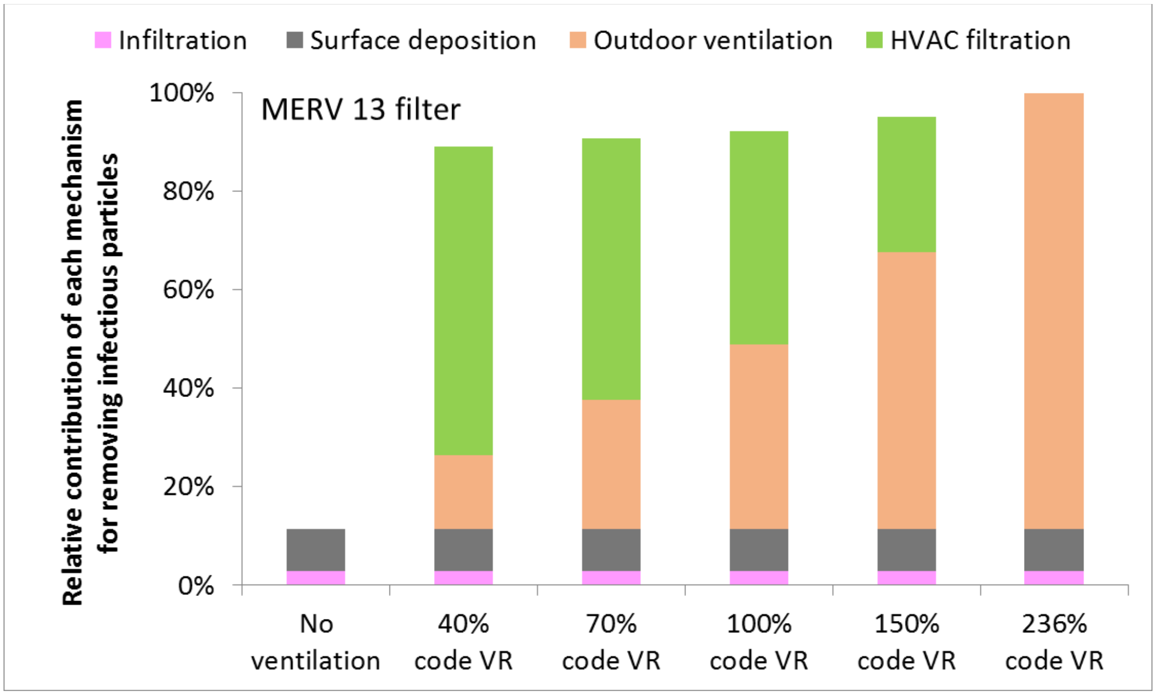
Infiltration
Surface deposition
Outdoor ventilation
HVAC filtration
MERV 4 filter
Relative contribution of each mechanism for removing infectious particles
100%
80%
60%
40%
20%
0%
No ventilation
40% code VR
70% code VR
100% code VR
150% code VR
236% code VR

(a)



Infiltration
Surface deposition
Outdoor ventilation
HVAC filtration
MERV 8 filter
Relative contribution of each mechanism for removing infectious particles
100%
80%
60%
40%
20%
0%
No ventilation
40% code VR
70% code VR
100% code VR
150% code VR
236% code VR

(b)



(c)

Figure 5. Relative contributions of each mechanism for removing SARS-CoV-2 virus-containing particles with increased levels of HVAC filtration in a hypothetical classroom under various ventilation rates (VR), based on input parameters defined in Tables 3 and 4 and other default values defined in this paper, with the maximum removal rate achievable under 236% of the code-required VR (100% outdoor air) defined as 100%: (a) MERV 4 filter; (b) MERV 8 filter, and (c) MERV 13 filter.

Results illustrate that the total infectious particle removal (thus RR reduction) from increasing VRs depends on the efficiency of the HVAC filters: increasing VRs lead to greater risk reductions for systems with low efficiency filters than for those with high efficiency filters. For example, increasing VR from 40 percent of the code-required VR to 100 percent outdoor air enhanced infectious particle removal by a factor of 3.3 (i.e., from 30 percent to 100 percent) when a MERV 4 filter is installed, whereas for a MERV 13 filter removal changed only by a factor of 1.1 (i.e., from 89 percent to 100 percent).

Figures 5a to 5c also clearly show the increased contribution of filtration to the total infectious particle removal as filter efficiency increases, especially under poor ventilation conditions. For example, for the cases with 40 percent of the code-required minimum VR, the estimated contribution of filtration to the total infectious particle removal for the hypothetical classroom defined in this paper was 4 percent, 34 percent, and 63 percent of the maximum possible removal rate for MERV 4, MERV 8, and MERV 13 filters, respectively.

Again, we note that all these results are rough estimates of infection probability due to assumed long-range, airborne viral transmission, using simplified hypothetical scenarios. The *proportional contributions* of long-range airborne transmission vs. close-range droplet and surface transmission to total infection risk is an important yet challenging question beyond the scope of this work.

Discussion

Here we present an illustrative model of how changing ventilation rate (VR), air filtration, and mask-wearing practices, each alone or in combination with the others, can alter the estimated relative probability of infection from long-range, small aerosols, in conditions that represent California classrooms. Broadly, the results demonstrate that any of these interventions, compared to none, reduces the estimated probability of infection by long-range, small aerosols. Other researchers have discussed a similar concept of integrating indoor air quality[96] control strategies to reduce the risk from asymptomatic SARS-CoV-2 infections in classrooms[79] and to reduce viral aerosols indoors more generally.[127]

Ventilation and filtration–combined effects and relative contributions

The model results demonstrate that ventilation can play an important role in reducing long-range, airborne viral transmission. Failure to increase the current VRs in California classrooms, often substantially below the Title 24 minimum code requirement,[116,124] is estimated to result in a 10–20 percent increased probability of infection from small aerosols (1a and 2a in Figure 3), relative to the reference compliance case. The extreme case of "no ventilation" could increase the probability of infection by over 500 percent (E-I in Figure 4). This benefit is recognized in some guidelines, which recommend maximizing outdoor air ventilation for HVAC systems with fixed total air supply.[43]

The model also shows that effective air cleaning/filtration, installed and operated properly, can substantially reduce the probability of airborne viral transmission. Guidelines from multiple other groups emphasize the importance of using adequately efficient filters such as MERV 13 or higher, properly installed and maintained, to most effectively remove infectious agents from recirculated HVAC air.[14,15,41,43,45,106,125,147,148] A different recommendation comes from one European source: because of skepticism that the filtration generally used would be adequate to ensure safe recirculated air, they recommend 100 percent outside air.[148] Because provision of 100 percent outdoor air is not practical for many U.S. HVAC systems, effective filtration of recirculated air is essential. Proper selection, installation, and maintenance of HVAC filters are all essential to achieving the desired particle filtration benefit. The higher the MERV rating of installed filters, the safer, within the feasibility limits of system compatibility and cost. The ASHRAE guidance for school reopening recommends installation of MERV 13 or better filters, where possible, for the best current balance between effectiveness and feasibility.[41]

Although the combined improvement of ventilation and filtration can always reduce long-range airborne transmission, the transmission reduction from each of three strategies–increasing ventilation, improving HVAC filtration, and adding in-room particle filtration–depends on the values of the others (as well as on other model assumptions; e.g., size distribution of virus-containing particles, filter removal efficiency, and recirculated airflow rate).

In our results, more efficient HVAC filters reduce risk more when VRs are lower, because (assuming fixed total air flow) recirculated airflow rates are then higher and recirculated air is filtered repeatedly. Thus, in the simulated scenarios, the contribution of a given HVAC filter to overall risk reduction gradually decreases as VR increases. At a given VR, risk reduction from increasing MERV 8 to MERV 13 is only marginal (10 to 40 percent), because even a MERV 8 filter is efficient at removing the particle sizes that the current model specifies as most likely to contain virus. If instead, an infectious particle size distribution with viruses primarily in smaller particles is assumed, model results would show a larger benefit from upgrading to a MERV 13 filter

As for the choice between upgrading the HVAC filter and adding portable air cleaners, for many of the ventilation scenarios modeled in this paper, the use of AHAM-sized portable air cleaner(s) in addition to standard MERV 8 HVAC filters reduced the relative infection probability approximately 20 percent more than upgrading to a MERV 13 filter. However, it should be noted that multiple portable air cleaners probably would be needed in each classroom to meet AHAM's 2/3 rule.[130] In addition, the relative impacts of HVAC filtration can be greater if the HVAC system provides a higher recirculating airflow rate than assumed in our modeled scenarios, in which case the overall HVAC filter particle removal rate would increase and may make it more protective than portable air cleaners.

Practical considerations for ventilation and filtration

VRs below code requirements[116,124] have implications for the transmission of viruses and other infectious agents more broadly, and these results suggest that disease transmission occurring through small airborne particles might be reduced if California classrooms consistently met code requirements during occupancy. As part of a larger focus on improving VRs in schools, several sources have recommended installation of carbon dioxide (CO_2) sensors to verify that proper ventilation is maintained throughout the school year.[125] Continuous measurement of CO_2 is useful as it provides a real time, direct measure of the accumulation of occupant-emitted bioeffluents, as well as an indication of the amount of outdoor air that the ventilation system delivers per person.

Title 24–2019 Building Energy Efficiency Standards requires use of MERV 13 filters or greater for all new systems and constructions.[118] Therefore, upgrading filters to MERV 13 may be a long-term strategy for particle filtration for classrooms with mechanical ventilation systems, and should be considered before adding portable air cleaner(s). However, portable air cleaners may play an important role if there is no mechanical ventilation (e.g., classrooms with only openable windows) or when outdoor air pollution, such as wildfire smoke, is high.[149] With wildfires predicted to recur regularly in California's future, schools would benefit from preparing alternatives to outdoor air ventilation, such as air filtration, for these situations. Still, caution should be used when selecting air cleaning/filtration products. Some types of air cleaning devices, although commercially available and marketed as effective and safe for use indoors in response to the COVID-19 outbreak, have unproven efficacy, and some (i.e., ozone generators and ionization devices) may even produce harmful pollutants.[150,151] CARB strongly advises against the use of ozone generators in occupied spaces and provides a list of potentially hazardous ozone generators sold as "air purifiers." CARB also provides a list of approved air cleaning devices, certified for electrical safety and low (usually near-zero) ozone emissions.[150,151] When considering air filtration devices, it is best to select only devices that have MERV or CADR ratings.[150]

Only limited cost-benefit analysis has been done for the various intervention strategies included in these scenarios.[127,152] It would be useful to further research the ease of implementation and relative costs of these strategies in order for school districts to identify the most economical way to achieve the same risk reduction and other IAQ benefits.

Mask use

In our model, we treated mask use only as a strategy for contaminant source control (not as personal protective equipment, PPE), and assumed that mask reduced infectious particle emissions by 50 percent. Thus, without changing anything about a classroom, infection probability was reduced by half if teachers and students followed this recommendation. Our estimation is conservative because more effective face masks could further decrease this probability of infection.[82,140,153] Moreover, masks may also provide a personal protective benefit by filtering out some of the indoor airborne aerosols before they are inhaled, a benefit which has not been included in our model. For each assumed VR, the lowest probability of infection was observed when *some form of enhanced air filtration and masks were both used*. It should be noted that these estimates do not include additional risks from any close-range exposure to small and large respiratory droplets, currently considered a primary transmission route for SARS-CoV-2. For such close-range exposure, face masks can play an even more important role in reducing the probability of infection—more effectively than ventilation or filtration, which remove only long-range, small aerosols. In addition, face masks interrupt the transmission of viral fomites from surfaces to hands and then to the nose or mouth. Overall, our analysis supports the most recent California school reopening guideline, requiring face coverings for students in 3rd grade through high school and for all teachers and staff,[154] as well as advice from CDC.[155]

Further modeling efforts

There are other recently released modeling tools. The U.S. National Institute for Standards and Technology (NIST) has released a web application (*Fate and Transport of Indoor Microbiological Aerosols [FaTIMA]*).[141] It allows more input parameters and supports more complex dynamic behavior analysis of indoor microbiological aerosols associated with ventilation, filtration, deposition, and inactivation mechanisms. Results are presented as particle concentrations, not probability of infection. Additionally, a "SARS-CoV-2_*Airborne_Transmission_Estimator*" has been posted online, including a calculation spreadsheet for classrooms, and the benefit of mask wearing.[156] However, the estimation does not consider particle size and uses a lumped virus particle loss rate for all additional control measures without explicitly specifying its linkage to the MERV rating of an HVAC filter or the CADR of portable air cleaners.

The model described in this paper can also be adjusted to include virus deactivation via other technologies. It has recently been highlighted how vulnerable the SARS-CoV-2 virus is to ultraviolet radiation.[157-159] The use of ultraviolet germicidal irradiation (UVGI) as a potential air disinfection strategy, either within a room as upper air irradiation or within an HVAC system to treat recirculated air, is an active area of research, and UVGI application for SARS-CoV-2 reduction warrants further evaluation.[6,29,160] See Appendix 4 for estimates of irradiance requirements for SARS-CoV-2 and further discussion of UV applications.

Comparing results from these various models and further improving the model presented in this paper would allow confirmation and more accurate estimation of relative infection risk for various scenarios, and more broadly, greater understanding of how managing buildings and the behavior of people in school classrooms can affect that risk.

Conclusions

New research and reports on the spread and control of COVID-19, both in general and for school environments in particular, are being published continuously and our understanding of its transmission and effective control measures are growing. Here, we have taken an existing model of aerosol disease transmission and adapted it for the SARS-CoV-2 virus, using currently available information. Although simplified in its approach, the model highlights the potential impact from different classroom interventions (e.g., face masks, ventilation, and air cleaning) as a tool for prioritizing strategies, providing insights relevant to COVID-19 as well as to other airborne contaminants in California classrooms and elsewhere.

Our results demonstrate that classroom interventions, including ensuring HVAC system operation to meet the Title 24 code-required minimum ventilation rate (i.e., through testing and adjusting ventilation system equipment and continuous CO_2 monitoring) and providing enhanced particle filtration (i.e., through HVAC systems or AHAM-sized portable air cleaners), have the potential to reduce the probability of respiratory infections that could occur through long-range, small aerosols. Further planned activities with other California agencies and field HVAC experts include promoting such interventions and conducting post-reopening surveys on school operation and maintenances.

In this paper, we also briefly demonstrate the substantially decreased infection risk if classroom occupants wear masks to reduce infectious emissions. However, these estimates do not account for the multiple other benefits masks provide, which together could be as large or larger: reducing close-range exposure to small and large respiratory droplets, reducing deposition of droplets onto surfaces, preventing wearers from touching their noses and mouths, and also providing a personal protective benefit by filtering out some indoor airborne particles before they are inhaled. It is beyond the scope of this paper to quantify all of the advantages and disadvantages of mask wearing in school environments. As a general guiding principle, source control (such as excluding symptomatic persons from schools, covering coughs, and wearing masks during respiratory infections) should always be considered first to minimize disease transmission.

Finally, this paper mainly addresses airborne viral transmission, for which ventilation and filtration play important roles in reducing infection risk. For SARS-CoV-2 specifically, we acknowledge the great uncertainty of whether and how significantly long-range airborne transmission contributes to overall infection risk, and we support the use of other appropriate control/prevention strategies (e.g., social distancing, wearing masks, and intensified cleaning and disinfection) that have been widely addressed in other published guidance documents on reducing disease transmission during the COVID-19 (or SARS-CoV-2) pandemic.

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SUMMARY OF ASHRAE'S POSITION ON CARBON DIOXIDE (CO_2) LEVELS IN SPACES

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Purpose of the Summary Statement:

It is widely reported by the technical community involved in indoor air evaluations that the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) has a standard of 1,000 ppm CO_2 for indoor spaces. The Standard often cited is ANSI/ASHRAE 62-1989 "Ventilation for Acceptable Indoor Air Quality" (which has since been replaced by ANSI/ASHRAE 62-1999). However, this interpretation is incorrect.

The purposes of this Summary Statement on Carbon Dioxide Levels is to provide background and information on the basis of the "1,000 ppm CO_2" *guidelin*e value and how it was intended to be used regarding indoor air quality. As will be discussed below, this "1,000 ppm CO_2" value is not contained in the latest ANSI/ASHRAE 62-1999 standard.

Background:

One of the best papers addressing this issue was prepared by Mike Schell and Dan Int-Hout entitled "Demand Control Ventilation Using CO_2" published in the February, 2001, ASHRAE Journal (copy attached as Attachment A). This article points out that CO_2 has long been used as a basis for ventilation (providing fresh outdoor air to indoor spaces) design and control. CO_2 is a natural product of human respiration whose rate can be predicted based on an occupant's age and activity level. Beginning as early as 1916 (*Mechanical Engineer's Handbook* by McGraw-Hill) and found in the New York City Building Code of 1929, CO_2 of 800 to 1,000 ppm and 1,000 ppm respectively were recommended. *However, the key point is that CO_2 levels are good predictors or surrogates for human emitted bioeffluents (i.e., odors) that are considered undesirable for the overall human comfort inside conditioned spaces.* Thus CO_2 is a surrogate for levels of other bioeffluents that cause odors that are likely to be viewed as unacceptable by others in the space, not because of their presence as a direct health hazard.

It is helpful to review the basis for the 1,000 ppm CO_2 as well as the language in the ANSI/ASHRAE 62-19<u>89</u> standard and Interpretation Documents from ASHRAE on this matter.

The 1,000 ppm guideline value for CO_2 used in the 1989 standard was based on an assumed ventilation air (outdoor air) rate of 15 CFM/person and an outdoor baseline CO_2 concentration of 300 ppm. (Note that the 1999 standard set a differential CO_2 level of 700 ppm along with minimum ventilation rates for given spaces rather than an absolute value like 1,000 ppm. This change to the standard occurred because background CO_2 levels are closer to 400 ppm than 300 ppm resulting in an indoor level of 1,100 ppm CO_2 using the same 15 CFM/person as was used in the 1989 standard. Thus the current standard would have a baseline above 1,000 ppm CO_2. Moreover, as will be discussed, this absolute value led to confusion in the design, and health and safety communities.)

Specific language contained in the 1989 standard are reproduced below:

Section 6.1.3: "Human occupants produce carbon dioxide, water vapor, particulates, biological aerosols, and other contaminants. Carbon dioxide concentration has been widely used as an indicator of indoor air quality. Comfort (odor) criteria are likely to be satisfied if the ventilation rate is set so that 1000 ppm CO_2 is not exceeded. In the event CO_2 is controlled by any method other than dilution, the effects of possible elevation of other contaminants must be considered."

Section 6.2.1: Repeats the Section 6.1.3 language of the standard.

Table 3: "Guidelines for Selected Air Contaminants of Indoor Origin"

Contaminant	Concentration	ppm	Exposure Time	Comments
Carbon Dioxide	1.8 g/m^3	1000[a]	Continuous	See App. D

[a] This level is not considered a health risk but is a surrogate for human comfort (odor). See Section 6.1.3 and Appendix D.

This last statement clearly defines the role of CO_2 in the standard.

ASHRAE also produced a document entitled "Interpretations for ASHRAE Standard 62-1989 Ventilation for Acceptable Indoor Air Quality" that provided specific interpretations of this standard. Two questions, and their responses, (see Attachment B) are directly relevant to this current topic and confirm the last statement just discussed.

Q: June 26, 1995 – The carbon dioxide level of 1000 ppm noted in 6.1.3 and 6.2 including Table 3 appears to be provided as a recommended guideline rather than a mandatory requirement. Can the carbon dioxide level in a space ever exceed the referenced value of 1000 ppm, and still remain in compliance with the standard?

A: Yes. The CO_2 level of 1000 is a guideline for comfort acceptability, not a ceiling value for air quality.

A similar series of questions on the topic were responded to on January 29, 1995:

Ms. Paolini, Manager of Health and Safety notes that….It is unclear what is meant by the clause, "ventilation rate is set so the 1000 ppm CO_2 is not exceeded."

Q1: Is the 1000 ppm CO_2 a ceiling value or a time weighted average value?

A1: The reference to 1000 ppm CO_2 in Section 6.1.3 is only as a point of information. This is not a requirement of ASHRAE 62-1989. Since it is not a requirement it is neither a ceiling nor a time weighted average value. Rather, it can be considered a target concentration level. Since comfort (odor) criteria are likely to be satisfied when the CO_2 does not exceed 1000 ppm the converse is also likely to be true, i.e., when the CO_2 level exceeds 1000 ppm, the comfort (odor) criteria may not be satisfied.

Q2: If it is a time weighted average value, how are the CO_2 test results to be calculated and weighted?

A2: Moot because of Answer 1.

Q3: Would CO_2 levels measured only during room occupancy be used or CO_2 levels measured throughout the time period of ventilation system operation?

A3: CO_2 levels should be measured during the time of occupancy. This is defined for the classroom as the time between initial occupancy in the morning and dismissal time for the students.

Again, these questions and answers suggest that the CO_2 level of 1,000 ppm is a guideline (surrogate for odors), not a standard.

One should note that the 1999 Standard has removed all mention of the 1,000 ppm value from the Standard.

Summary and Conclusions:

- The current ASHRAE Standard “Ventilation for Acceptable Indoor Air Quality” (ANSI/ASHRAE 62-1999) does not reference the term “1,000 ppm $CO_{2.}$”
- The former ASHRAE Standard “Ventilation for Acceptable Indoor Air Quality” (ANSI/ASHRAE 62-1989) references the term “1,000 ppm CO_2 as a surrogate for where human bioeffluents (odors) may be at levels not acceptable for human comfort. Further, this value of 1,000 is a guideline value only and not considered a regulated standard.
- Interpretation document questions and answers confirm this concept of the CO_2 concentration of 1,000 ppm as a guideline level to be used as a surrogate for odor causing compounds from human activity that may not be acceptable for human comfort.

If you have any questions or comments regarding this document, please contact the author at:

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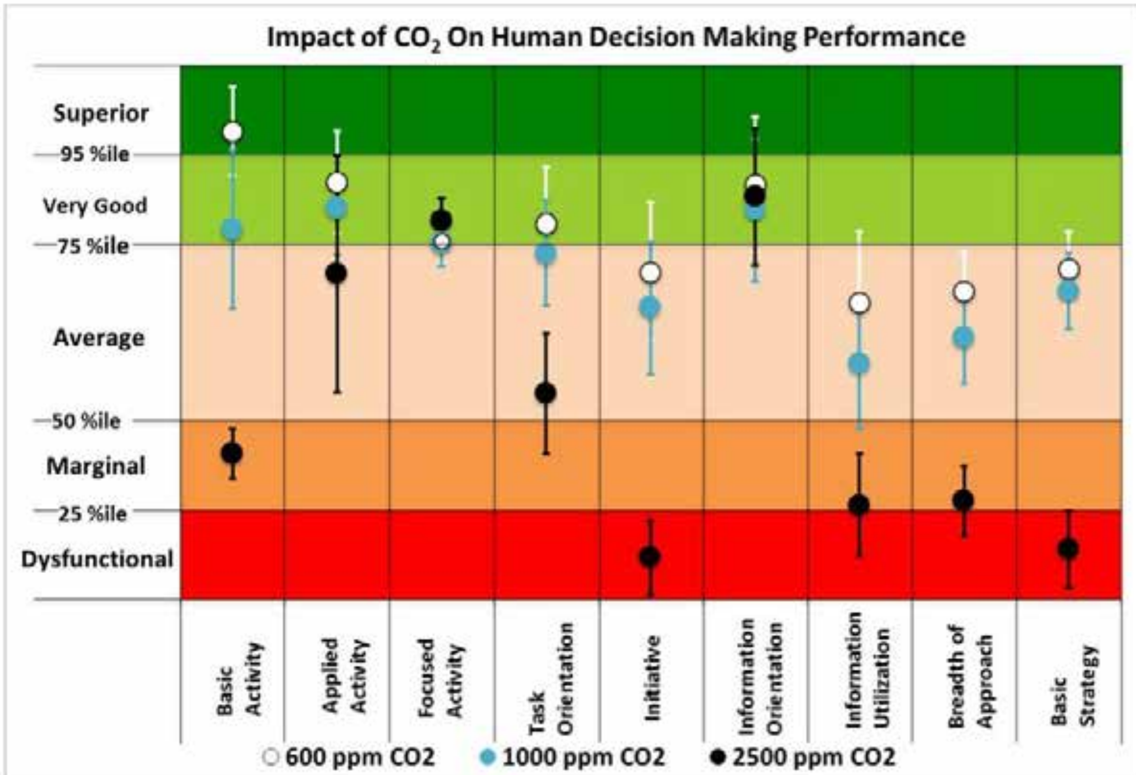
Elevated Indoor Carbon Dioxide Impairs Decision-Making Performance

Feature Story Julie Chao (510) 486-6491 • October 17, 2012

Overturning decades of conventional wisdom, researchers at the Department of Energy's Lawrence Berkeley National Laboratory (Berkeley Lab) have found that moderately high indoor concentrations of carbon dioxide (CO_2) can significantly impair people's decision-making performance. The results were unexpected and may have particular implications for schools and other spaces with high occupant density.

"In our field we have always had a dogma that CO_2 itself, at the levels we find in buildings, is just not important and doesn't have any direct impacts on people," said Berkeley Lab scientist William Fisk, a co-author of the study, which was published in *Environmental Health Perspectives* online last month. "So these results, which were quite unambiguous, were surprising." The study was conducted with researchers from State University of New York (SUNY) Upstate Medical University.

On nine scales of decision-making performance, test subjects showed significant reductions on six of the scales at CO_2 levels of 1,000 parts per million (ppm) and large reductions on seven of the scales at 2,500 ppm. The most dramatic declines in performance, in which subjects were rated as "dysfunctional," were for taking initiative and thinking strategically. "Previous studies have looked at 10,000 ppm, 20,000 ppm; that's the level at which scientists thought effects started," said Berkeley Lab scientist Mark Mendell, also a co-author of the study. "That's why these findings are so startling."



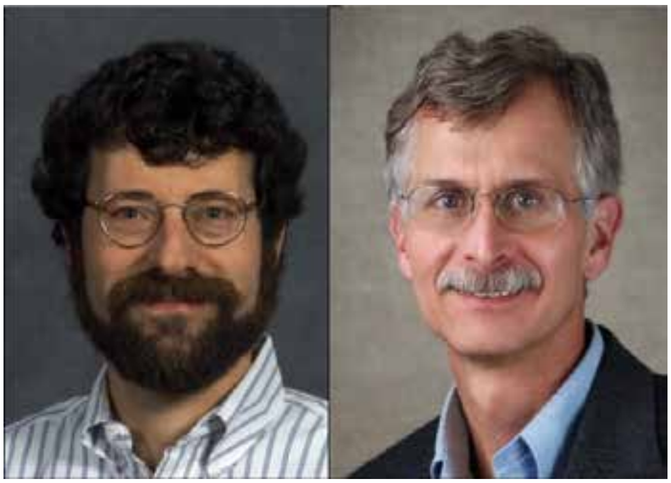
Berkeley Lab researchers found that even moderately elevated levels of indoor carbon dioxide resulted in lower scores on six of nine scales of human decision-making performance.

While the results need to be replicated in a larger study, they point to possible economic consequences of pursuing energy efficient buildings without regard to occupants. "As there's a drive for increasing energy efficiency, there's a push for making buildings tighter and less expensive to run," said Mendell. "There's some risk that, in that process, adverse effects on occupants will be ignored. One way to make sure occupants get the attention they deserve is to point out adverse economic impacts of poor indoor air quality. If people can't think or perform as well, that could obviously have adverse economic impacts."

The primary source of indoor CO_2 is humans. While typical outdoor concentrations are around 380 ppm, indoor concentrations can go up to several thousand ppm. Higher indoor CO_2 concentrations relative to outdoors are due to low rates of ventilation, which are often driven by the need to reduce energy consumption. In the real world, CO_2 concentrations in office buildings normally don't exceed 1,000 ppm, except in meeting rooms, when groups of people gather for extended periods of time.

In classrooms, concentrations frequently exceed 1,000 ppm and occasionally exceed 3,000 ppm. CO_2 at these levels has been assumed to indicate poor ventilation, with increased exposure to other indoor pollutants of potential concern, but the CO_2 itself at these levels has not been a source of concern. Federal guidelines set a maximum occupational exposure limit at 5,000 ppm as a time-weighted average for an eight-hour workday.

Fisk decided to test the conventional wisdom on indoor CO_2 after coming across two small Hungarian studies reporting that exposures between 2,000 and 5,000 ppm may have adverse impacts on some human activities.

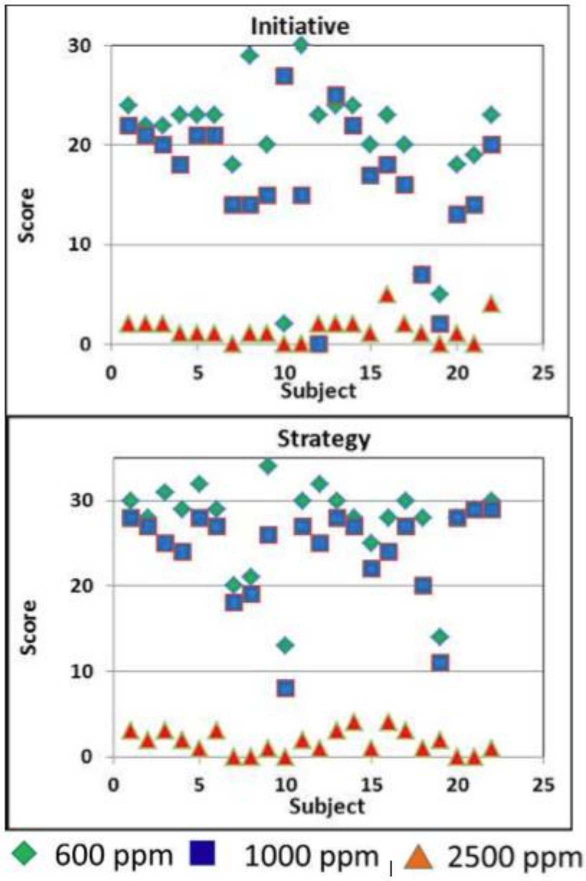


Berkeley Lab scientists Mark Mendell (left) and William Fisk

Fisk, Mendell, and their colleagues, including Usha Satish at SUNY Upstate Medical University, assessed CO_2 exposure at three concentrations: 600, 1,000 and 2,500 ppm. They recruited 24 participants, mostly college students, who were studied in groups of four in a small office-like chamber for 2.5 hours for each of the three conditions. Ultrapure CO_2 was injected into the air supply and mixing was ensured, while all other factors, such as temperature, humidity, and ventilation rate, were kept constant. The sessions for each person took place on a single day, with one-hour breaks between sessions.

Although the sample size was small, the results were unmistakable. “The stronger the effect you have, the fewer subjects you need to see it,” Fisk said. “Our effect was so big, even with a small number of people, it was a very clear effect.”

Another novel aspect of this study was the test used to assess decision-making performance, the Strategic Management Simulation (SMS) test, developed by SUNY. In most studies of how indoor air quality affects people, test subjects are given simple tasks to perform, such as adding a column of numbers or proofreading text. “It’s hard to know how those indicators translate in the real world,” said Fisk. “The SMS measures a higher level of cognitive performance, so I wanted to get that into our field of research.”



Strategic thinking and taking initiative showed the most dramatic declines in performance at 2,500 ppm carbon dioxide concentrations.

The SMS has been used most commonly to assess effects on cognitive function, such as by drugs, pharmaceuticals or brain injury, and as a training tool for executives. The test gives scenarios—for example, you're the manager of an organization when a crisis hits, what do you do?—and scores participants in nine areas. "It looks at a number of dimensions, such as how proactive you are, how focused you are, or how you search for and use information," said Fisk. "The test has been validated through other means, and they've shown that for executives it is predictive of future income and job level."

Data from elementary school classrooms has found CO_2 concentrations frequently near or above the levels in the Berkeley Lab study. Although their study tested only decision making and not learning, Fisk and Mendell say it is possible that students could be disadvantaged in poorly ventilated classrooms, or in rooms in which a large number of people are gathered to take a test. "We cannot rule out impacts on learning," their report says.

The next step for the Berkeley Lab researchers is to reproduce and expand upon their findings. "Our first goal is to replicate this study because it's so important and would have such large implications," said Fisk. "We need a larger sample and additional tests of human work performance. We also want to include an expert who can assess what's going on physiologically."

Until then, they say it's too early to make any recommendations for office workers or building managers. "Assuming it's replicated, it has implications for the standards we set for minimum ventilation rates for buildings," Fisk said. "People who are employers who want to get the most of their workforce would want to pay attention to this."

Funding for this study was provided by SUNY and the state of New York.

# # #

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Updated: February 18, 2015

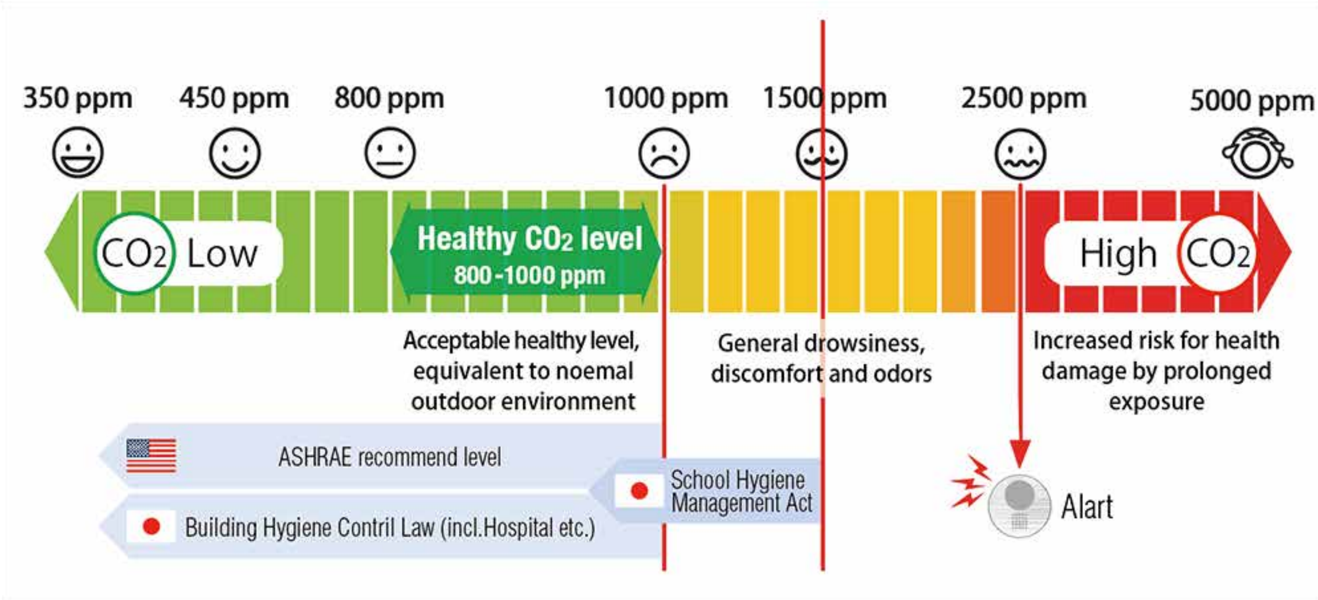
TAGS: buildings, indoor air

Guideline Chart on CO2 Levels

750-900 ppm CO2 would be good.

Most school clasrooms seem to be more like 1200-1800 ppm CO2

CO_2 [ppm]	Air Quality
2100	BAD Heavily contaminated indoor air Ventilation required
2000	
1900	
1800	
1700	
1600	
1500	MEDIOCRE Contaminated indoor air Ventilation recommended
1400	
1300	
1200	
1100	
1000	FAIR
900	
800	GOOD
700	
600	EXCELLENT
500	
400	


350 ppm
450 ppm
800 ppm
1000 ppm
1500 ppm
2500 ppm
5000 ppm
CO2 Low
Healthy CO2 level
800 -1000 ppm
High CO2
Acceptable healthy level, equivalent to noemal outdoor environment
General drowsiness, discomfort and odors
Increased risk for health damage by prolonged exposure
ASHRAE recommend level
School Hygiene Management Act
Building Hygiene Contril Law (incl.Hospital etc.)
Alart

Examining CO2 levels in school classrooms

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Topic A8: IAQ & perceived air quality

Examining CO_2 Levels in School Classrooms

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Keywords: Ventilation theory, Classroom ventilation, CO_2 levels, Air change rates (ACH)

SUMMARY

High CO_2 levels in school classrooms continue to be a concern. As a result we reviewed the mass-balance model of ventilation. We identified several factors by fitting the model to the data. The review allowed CO_2 build up, ventilation rates and exhalation rates to be examined in real (on-site) measured conditions.

We discuss the theoretical model of the growth and decay of CO_2 concentration in a space relates the model to the data through the parameters of the model, providing an understanding of the drivers of CO_2 concentration and some validation of the theory by the data. Results from our measurements of Australian school classrooms are similar to other parts of the world, indicating CO_2 levels, ventilation rates and air temperatures do not comply with the standards.

INTRODUCTION

This paper utilizes the results of the MABEL (Mobile Architecture and Built Environment Laboratory) facility project, which measured several school classrooms for their CO_2, comfort index and temperature stratification levels (Luther and Atkinson, 2012). These Australian results confirm what has been discovered elsewhere internationally, that school classrooms frequently suffer poor indoor air quality, ventilation and comfort control. In an effort to remedy these problems, as found in our evidence-based study, this paper begins first by understanding the build up and decay of CO_2 in the provided cases.

A broad range of studies shows that ventilation rates in schools are inadequate (Mendel and Heath, 2005). What is controversial is the number of air changes required to ventilate classrooms to achieve acceptable levels of CO_2 and pollutants. Perhaps the causes of this are the various units and methods of determining ventilation air change rates as well as a misinterpretation of the standards. The ASHRAE Standard 62.1-2004 (ASHRAE 2004) recommends a minimum of 8L/sec per person for classrooms. Depending on classroom size, and volume this amount could typically result in between 3-5 ACH per classroom (Daisey et al. 2003 and Becker et al. 2007).

Achieving energy efficiency stands in opposition to controlling classroom air humidity, temperature and ventilation. Studies indicate improved student performance for elevated ventilation rates and reduced air temperatures in classrooms in summer (Wargocki and Wyon, 2006). These studies also observed CO_2 levels and found substantial reductions using ventilation rates of 6.5 and 9.5L/s/person, yielding 900ppm and 780ppm respectively. Other researchers confirm that rates of 7 – 10 L/s/person are required to reduce TVOC's and other pollutants (Fischer and Bayer, 2003 and Daisey, et al., 2003). Further studies confirm that air quality symptoms increased at a ventilation rate below 10L/s/person (Seppanen et al., 1999). Our review suggests that more accurate calculations accounting for the number of people, their activity and the room volume as well as the air change rate, can be performed.

The above work of others and our measurement studies of several Australian school classrooms prompted several questions. What is a reasonable respiratory (CO_2 generation) rate for a typical student? How does the air change rate affect the CO_2 levels over time? What influence does room volume have on the level of CO_2 for a given condition? In search of answers to these questions we began to review the fundamental mass-balance equations.

METHODOLOGY

We present the theoretical model of CO_2 concentration in detail so as to clarify the roles of the quantities involved. The general solution shows the relationships between the key parameters.

Ventilation Standards and Theoretical Model

Previous work suggests that the first step in designing for ventilation is to calculate the ventilation requirements with respect to the acceptable indoor air quality. Various national and international standards exist, which give guidance on required fresh air design rates, but the sources offer inconsistent advice. However, all agree that schoolrooms, due to the number of occupants, require more dilution air than adult occupants in a similar space. The range of values suggested in the standards is from 6.25 to 15L/s/person (AS 1668.2-2002 and EN 13779 2007).

In order to determine what a ventilation rate should be for a particular case the parameters involved in causing high CO_2 levels must be understood first. We are interested in understanding how CO_2 concentration changes in a confined space. This change occurs at any instant at rates determined by the ventilation rate and the number of occupants in a known volume. Given a volume, CO_2 enters it at a rate determined by the outdoor CO_2 concentration, C_{ext}, and leaves it at a rate determined by the indoor CO_2 concentration at time t, C(t). In addition, people add CO_2 to the air in the room at rates estimated from physical measurements (Figure 1).

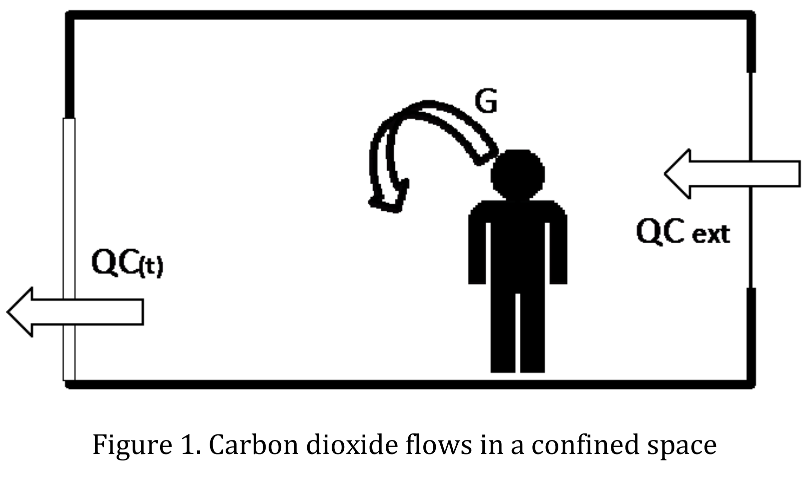

Figure 1. Carbon dioxide flows in a confined space

This is summarized in Equation (1) in which the rate of adding CO_2 less the rate of exhausting CO_2 causes the concentration of CO_2 in the volume to change. This equation expresses the mass balance, the balance of CO_2 entering and leaving the volume at some instant, t:

$$V\frac{dC(t)}{dt} = G + QC_{ext} - QC(t) \tag{1}$$

where*

V = space volume in m^3
$C(t)$ = indoor CO_2 in ppm(v)
C_{ext} = outdoor, or ambient, CO_2 concentration in ppm(v)
t = time in s
G = indoor CO_2 generation rate in mL/s for a fixed number of occupants
Q = space ventilation rate in m^3/s
$\frac{dC(t)}{dt}$ = the rate of increase in the CO_2 concentration in ppm(v)/s

The rate of increase of CO_2 will be zero when $G + QC_{ext} = QC(t)$; that is, the CO_2 generated by people balances the CO_2 introduced and removed by ventilation. If this balance is achieved, as it will after a sufficient time, $C(t) = G/Q + C_{ext}$. This specific $C(t)$ is the steady state or final value of CO_2 concentration and we label it C_{ss}.

To allow for the number of people in the room, we define g and N in terms of G as follows:

$$G = Ng \tag{2}$$

where N = the number of people in the space, and g = indoor CO_2 generation rate in mL/s per person. Hence,

$$C_{ss} = \frac{G}{Q} + C_{ext} = \frac{Ng}{Q} + C_{ext} \tag{3}$$

it is always true that $C_{ss} \geq C_{ext}$. Hence, $C(t)$ can never fall below the ambient concentration of CO_2, C_{ext}†.

Quite often, insufficient time is available for $C(t)$ to reach C_{ss}, and we need to know the transient behaviour of $C(t)$; that is, how $C(t)$ changes before settling. Furthermore, it may be that the space is not initially in equilibrium with the environment. The solution to the above Equation (1), satisfying initial and final values, is the exponential equation:

$$C(t) = (C_{ss} - C_{t0})\left(1 - e^{-\frac{Qt}{V}}\right) + C_{t0} \tag{4}$$

where C_{t0} is the actual CO_2 concentration at $t = 0$.

---

* Note that $1 mL/m^3$ = 1 ppm(v).

† We ignore the unrealistic case in which, initially, CO_2 is absent from, or reduced in, the indoor air, as it will eventually rise to the ambient concentration, C_{ext}, of CO_2.

The air change rate is in fact the quotient Q/V represented by the symbol a. Its reciprocal, $\tau = V/Q$ is the time constant of Equation (4). This is the time required to change one air volume in the space considered. It is important to understand that the concentration of CO_2 as time passes is determined by knowing the values of three parameters, its initial concentration, C_{t0}, final concentration, C_{ss}, and the air change rate, a. Of course, these values may change in response to external or internal influences, changing the behaviour of $C(t)$.

Substituting aV for Q and rearranging Equation 3,

$$\frac{Ng}{V} = a(C_{ss} - C_{ext}) \tag{5}$$

it is clear that the three quantities determining the concentration curve that are on the right of the equation are also related to the quantity Ng/V. This quantity is the rate at which people add to the CO_2 concentration in the space. That is, the number of people in the room, their average CO_2 exhalation rate and, inversely, the room volume combine to offset exfiltration reducing CO_2 concentration to the background value.

An example of modelling various air change rates, by applying the previous equations to a space with a constant CO_2 generation rate and fixed volume is shown in Figure 2. Note that the time-constant, $\tau = 1/a$, differs for each curve as a changes, as does the final value, C_{ss}. If the air change rate, a is small, the time-constant, τ, and the final value, C_{ss}, are large. The concentration of CO_2 takes a long time to settle to a large value. On the other hand, if a is large, the time-constant, τ, and the final value, C_{ss}, are small, and the concentration settles quickly to a small value, closer to C_{ext}.

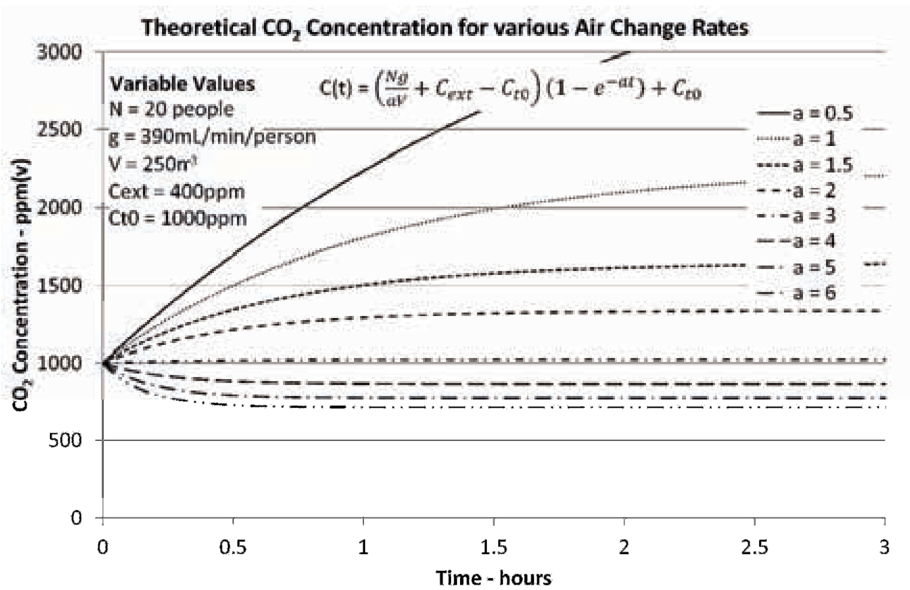

Figure 2. CO_2 Concentration for Various Air Change Rates in a Classroom

Establishing a Target Value of Classroom CO_2

According to the NISTIR 6729 report by Emmerich and Persily (2001), carbon dioxide is not generally considered to be a health problem. A limit for an 8 hour exposure and a 40 hour work week is 5000 ppm(v) and a short 15 min exposure limit is 30,000 ppm(v).

A major driver for investigating CO_2 build up in school classrooms is discomfort, leading to learning difficulties. Several publications by the World Health Organisation (WHO) and ASTM D6245 (2002) recommend an upper limit value of 1000 ppm. Furthermore, studies have been conducted to investigate the Predicted Percentage Dissatisfied (PPD) with CO_2 concentrations indicating that a 25% PPD begins at around 1000 ppm. It must be noted that this figure is concentration *above* outdoor CO_2 levels, indicating that ~1,400 ppm would be the accepted value at 25% PPD. These findings have also been confirmed in the publications of Olesen (2004).

Estimating CO_2 Generation within a Classroom

Since we are interested in the removal of CO_2 we need to know at what rate this is being generated. Results presented in Plowman & Smith (2007) and Emmerich & Persily (2001) for an activity level of 1.5 met indicate a CO_2 production level of 0.0065 L/sec, or 390 mL/min. However, it should be noted that these values are for adults and are therefore conservative. Plowman & Smith report a tidal volume range of 6–90 L/min from which a typical tidal volume of 20 L/min might be assumed. The exhaled CO_2 concentration is about 4.5% or 900 mL/min. ASTM D6245 (2002) suggests the CO_2 generation rate of a child with a physical activity level of 1.2 met is 0.0029L/s. For an adult this this is 0.0052 L/s (320 mL/min). In Figure 2, the CO_2 generation rate per student is assumed to be 300mL/m/person, but we intend to investigate this parameter more closely from our measurement data.

RESULTS AND DISCUSSION

We studied 24 classrooms in four different schools during a winter period in Victoria Australia (a cool temperate climate) with different building construction types. No classroom had room conditioning during the measurement period. It is clear that CO_2 levels can increase rapidly in a typical occupied non-ventilated room as shown, for example, in **Error! Reference source not found.**. Furthermore, the opening of a door copes with this problem easily during a break, indicating that a proper cross-ventilation will reduce CO_2 levels dramatically.

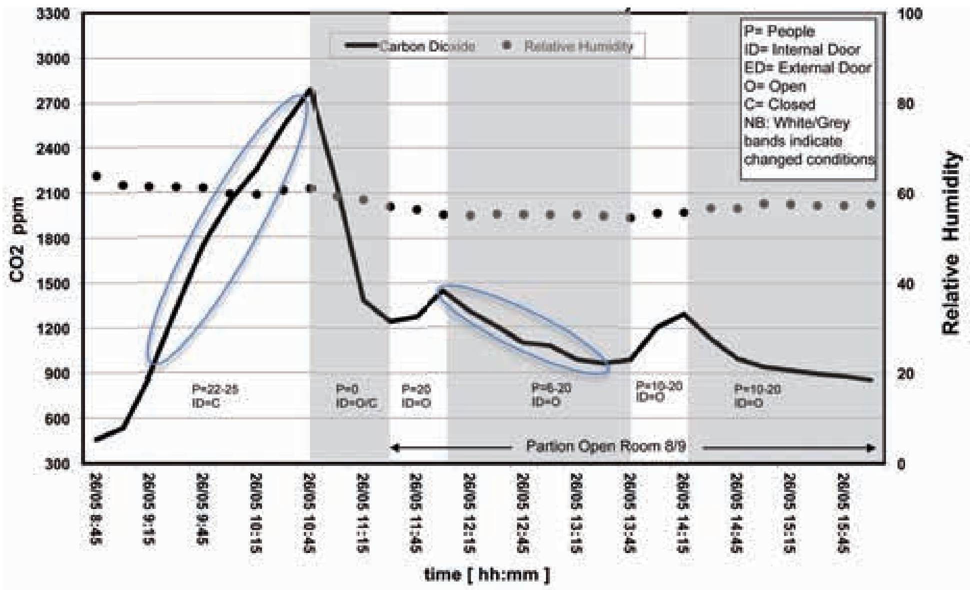

Figure 3. CO_2 and Humidity Levels in a Single Classroom

We need to fit the theoretical model to the data to identify the parameters a, C_{ss} and C_{t0} in Equation (4) because the CO_2 concentration rarely settles to steady values. Indeed, there is no point in Figure 3 which has reached a steady state. Given these values, we can then determine the factor Ng/V, and hence the CO_2 exhalation rate, g.

The fit of the model to seven points from 9:15 to 10:45 (left ellipse in Figure 3) is shown in Figure 4. From Equation (5), $Ng/V = 2193$ ppm/hour. Assuming a room volume of 250m^3 and that there are 22 – 25 people in the room, as recorded, for 25 people, $g =$ 366 mL/person/minute.

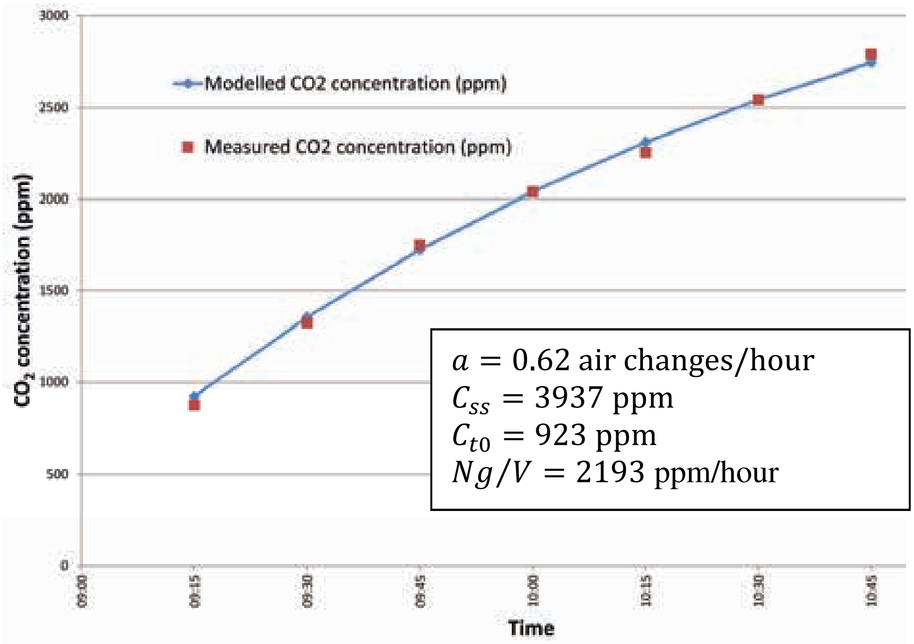

Figure 4. Door closed, room occupied

The fit of the model to the later seven points from 12:00 to 13:30 (right ellipse in Figure 3), is shown in **Error! Reference source not found.**. In both cases, the room is closed and the air change rate is 0.62 which is close to 0.60 for the earlier fit. This is a good validation of the model. Hence, $Ng/V = 75$ ppm/hour. However, the number of people recorded is 6 – 20 and the internal partition between this and the adjacent classroom is now open, so the room volume is now 500m^3. This yields $g = 104$ mL/person/minute for 6 people, a figure too low which needs further investigation.

CONCLUSIONS

We have reviewed a number of papers which show that ventilation rates in schools are inadequate and that the required air change rate to achieve acceptable levels is controversial. As a result, we have gone back to the theoretical foundations of ventilation. Although this theory is long-standing, insights from it have proved valuable.

We have explored the behaviour of CO_2 concentration in a room as a function of time, room volume, the number of people present and their exhalation rate of CO_2, the air change rate, the initial concentration of CO_2 and its background concentration. As a result, we have fitted the function to the data in a number of cases, of which we have shown two fits from the same room. This shows a consistency in the value of the air change rates required to fit the model to the data, validating our approach. Having fit the data, we have then been able to estimate the exhalation rate, but this is not as consistent and needs further investigation.

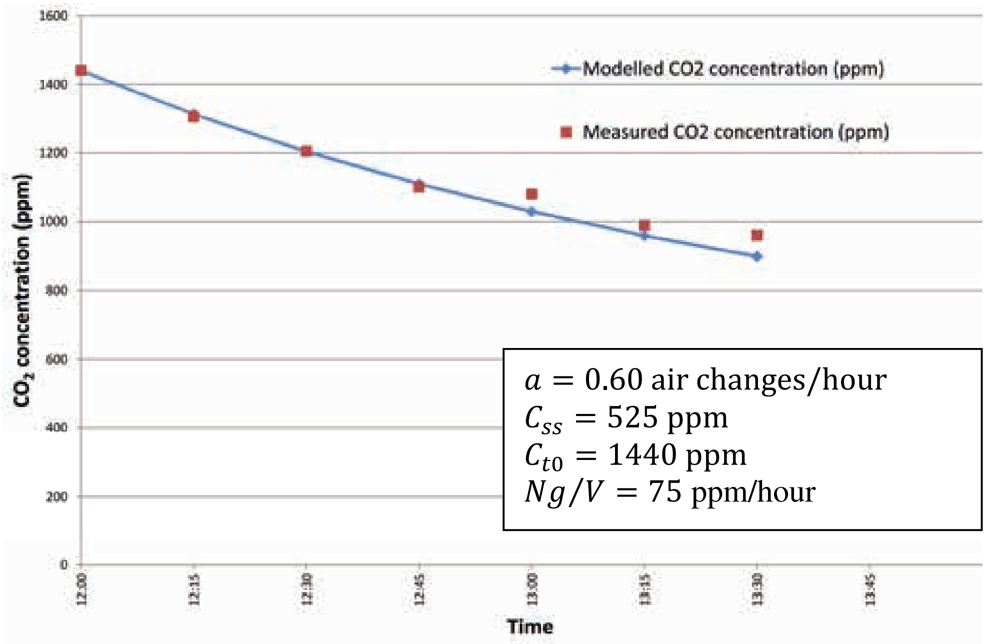

Figure 5. Door closed, at most six people

Having made a fit by adjusting the parameters a, C_{ss} and C_{t0} in Equation (4) to minimize the mean square error of the theoretical data point to the measured data point, a good estimate of Ng/V and therefore g may be determined since N and V are known.

Re-examining the equations of ventilation theory and fitting measured data have provided important insights. The causes and rates of CO_2 generation within a room are better understood. In particular, the rate at which CO_2 is exhaled per student in a classroom under typical user conditions can be better identified. Also, the study of air change rates and their influence on CO_2 reduction is applicable to HVAC ventilation system design. It is important to recall that this investigation considered non-mechanical, passive ventilation of classrooms. These passive air-change rates could be increased through mechanical means if necessary.

Furthermore, the observation that it takes time to reach a particular CO_2 level in the real-world classroom, where nothing remains constant for a long period of time, can mean that active ventilation can be delayed until a threshold concentration is reached, saving energy.

Lastly, since we have a method for investigating ventilation which identifies the relevant parameters from data, we have a model which can be used for prediction. Working in reverse, the variation of concentration of CO_2 can be predicted as a function of time, as N and the room conditions change. This work is yet to be reported. We intend to make further findings from our case study measurements, including advice for HVAC design and control.

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Air pollution and detrimental effects on children's brain. The need for a multidisciplinary approach to the issue complexity and challenges

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Millions of children in polluted cities are showing brain detrimental effects. Urban children exhibit brain structural and volumetric abnormalities, systemic inflammation, olfactory, auditory, vestibular and cognitive deficits v low-pollution controls. Neuroinflammation and blood-brain-barrier (BBB) breakdown target the olfactory bulb, prefrontal cortex and brainstem, but are diffusely present throughout the brain. Urban adolescent Apolipoprotein E4 carriers significantly accelerate Alzheimer pathology. Neurocognitive effects of air pollution are substantial, apparent across all populations, and potentially clinically relevant as early evidence of evolving neurodegenerative changes. The diffuse nature of the neuroinflammation and neurodegeneration forces to employ a weight of evidence approach incorporating current clinical, cognitive, neurophysiological, radiological and epidemiological research. Pediatric air pollution research requires extensive multidisciplinary collaborations to accomplish a critical goal: to protect exposed children through multidimensional interventions having both broad impact and reach. Protecting children and teens from neural effects of air pollution should be of pressing importance for public health.

Keywords: urban children, air pollution, cognition, brain volumetric changes, white matter hyperintensities, cytokines, Alzheimer, Parkinson

INTRODUCTION

In epidemiological studies, clean air has been linked to children's health and wellbeing (Newman et al., 2013; Amato et al., 2014; Barbieri et al., 2014; Liu and Lewis, 2014; Perera et al., 2014; Tang et al., 2014). Although most of the human studies have shown an associative link, experimental animal studies measuring exposure to specific components have shown a causal relationship between air pollution and an array of detrimental effects. Around the world, several metropolitan areas—but especially megacities (defined as areas of continuous urban development of over 10 million people, Kotkin and Cox, 2014)—now exceed the standards for air pollutants. Consequently, millions of children are at risk for or are already showing adverse short and long-term health outcomes, which include some of the most detrimental effects on brain development (Calderón-Garcidueñas et al., 2008; Brook et al., 2010; Guxens and Sunyer, 2012; Becerra et al., 2013). However, for the most part, current research and policy efforts link air pollution to respiratory and cardiovascular disease (Brook et al., 2010), and the effects on children's central nervous system (CNS) are still not broadly recognized. As a result, wide reaching public health initiatives targeting pediatric populations are still considered premature or unwarranted. One of the goals of this review is to show that contrary to a hesitant approach, there is enough evidence supporting the perspective that the effects of air pollution on brains of children and teens ought to be key public health targets.

In this paper, we briefly review current air pollutant standards, followed by epidemiological, clinical, and pathology studies associating air pollution exposures on children's brains concerning cognitive abilities, neurodevelopmental and neurodegenerative diseases. This overview puts forward common denominators for the mechanistic pathways linking air pollution to negative effects on the developing brain. Then, we turn to the outstanding challenges including the issues of how to formulate strategies to study *clinically healthy children exposed to air pollutants*, how to establish the links with the current mainstream concepts of cognition and neurodevelopment on one hand, and systemic inflammation, neuroinflammation, structural and volumetric brain changes and neurodegeneration on the other, followed by the ultimate goal to protect exposed children.

The present perspective indicates the need of a multidisciplinary approach, not only to address the issue complexity and challenges, but also to make developmental, behavioral and clinical researchers and practitioners aware of the wide spectrum of air pollution effects and the potential impact on their daily practice.

AIR POLLUTANTS: WHAT ARE THEY? WHERE ARE THEY?

In the US, the 1970 amendments to the Clean Air Act required the Environmental Protection Agency (EPA) to set National Ambient Air Quality Standards (NAAQS) for certain pollutants known to be hazardous to human health. EPA identified six criteria pollutants: ozone, carbon monoxide, particulate matter (PM), sulfur dioxide, lead, and nitrogen oxide and set the standards as a function of the characteristics and their potential health and welfare effects. In the US alone, more than 103 million people are exposed to PM concentrations above the standards, while 123 million are exposed to ozone. The two fractions of PM predominantly implicated in CNS effects are $PM_{2.5}$ (particles with a diameter $<2.5\ \mu m$) and ultrafine PM (UFPM) (particles with a diameter <100 nm). Most Outdoor $PM_{2.5}$, were generated from tailpipe and brake emissions from mobile sources, residential fuel combustion, power plants, wildfires, oil refineries, and metal processing facilities. The primary contributors to UFPM are tailpipe emissions from mobile sources.

Indoor air pollutants, including tobacco smoke, emissions from cook stoves, mycotoxins, plasticizers, flame retardants, and pesticides also represent a major source of harmful substances. Indoor air quality in schools is a major issue as the presence of mold, poor air quality, close proximity to major highways, and contaminated playgrounds can result in serious health problems (Everett-Jones et al., 2010; Sampson, 2012). Moreover, there are major disparities in indoor air pollution exposures related to socio-economic status (SES): the lower the SES, the higher indoor exposures (Adamkiewicz et al., 2011). Children are also exposed to manufactured nanoparticles (NPs) (>100 nm) in many consumer products including food, sunscreens and toothpaste (Linsinger et al., 2013).

ANIMAL MODELS OF OUTDOOR AIR POLLUTION COMPONENTS AND BRAIN EFFECTS

The complexity of the urban atmosphere makes it very difficult to establish a direct association of CNS effects with specific air pollutants in humans. Fortunately, animal models exposed to air pollutant components such as ozone, PM, diesel NPs, endotoxins, etc., have contributed a good deal to our understanding of the potential mechanisms acting upon the CNS. Depending on the pollutant component, doses, exposure protocol, age and gender, health status, etc., the detrimental effects range from endothelial dysfunction, breakdown of the blood-brain-barrier (BBB; Levesque et al., 2011), neuroinflammation (Fonken et al., 2011), formation of free radicals and oxidative stress (Guo et al., 2012), dopaminergic neuronal damage, RNA and DNA damage, to the identification of early hallmarks of Alzheimer and Parkinson's diseases (Brun et al., 2012).

In spite of the complexity, the evidence conclusively showed in animals that prenatal exposure to either one or a combination of criteria pollutants caused permanent changes in neurotransmitters and altered brain development, most commonly resulting in long-term deficits in functions associated with one or more memory systems (Takahashi et al., 2010; Fonken et al., 2011; Umezawa et al., 2012; Schröder et al., 2013).

CHILDREN'S SYSTEMIC AND BRAIN EFFECTS OF AIR POLLUTION

The detrimental developmental effects in animals are conceptually related to or even mirror the effects that might be expected and are actually observed in children. Consequently, it is reasonable and plausible to assume a fundamental continuity underlying the processes that impact the developing brain, in human or animal. In this section, selected possible mechanisms of the action of PM air pollution shown in **Figures 1**, **2** are specifically linked to key evidence found in Mexico City (MC) children.

Urban residents exhibit extensive respiratory inflammation that targets the nasal epithelium (Calderón-Garcidueñas et al., 1992). Severe mucosal changes translate in a breakdown of the nasal epithelial barrier facilitating the passage of xenobiotics to the systemic circulation and the brain, including PM both fine and ultrafine. The pulmonary damage is equally severe (Calderón-Garcidueñas et al., 2003), and boys are more affected than girls, likely because of longer daily outdoor activities (Villarreal-Calderón et al., 2002). Systemic inflammation and endothelial dysfunction with high production of endothelin-1 (ET-1) are also of importance. High concentrations of powerful inflammatory mediators such as interleukin-1β, tumor necrosis factor alpha (TNFα), and interleukin 6 (IL6) for which brain endothelial cells have receptors are present in the exposed pediatric populations. High ET-1 plasma concentrations, a very potent vasoconstrictor, negatively impact the brain microvasculature, resulting in hypoperfusion and ET-1 concentrations are directly associated with $PM_{2.5}$ exposures (Calderón-Garcidueñas et al., 2007).

Post-mortem neuropathology studies in children with accidental deaths comparing high vs. low pollution exposures revealed that 40% of urban children exhibited frontal tau hyperphosphorylation with pre-tangle material and 51% had $A\beta_{42}$ diffuse plaques compared with 0% in controls (Calderón-Garcidueñas et al., 2012a). Hyperphosphorylated tau (HPτ) and $A\beta_{42}$ plaques are hallmarks of Alzheimer's disease (AD; Braak and Del Tredeci, 2011). Of utmost importance for this review, children with the Apolipoprotein E allele 4 (a well-known risk factor for AD) had greater HPτ and diffuse Aβ plaques vs. E3 carriers, suggesting that genetic factors could make a significant portion of the exposed population more prone to accelerating their AD pathology (Calderón-Garcidueñas et al., 2012a). Arteriolar and capillary vascular changes with a diffuse breakdown of the BBB are at the core of the pathology in exposed children's brains. The changes are significant in the olfactory bulb and the prefrontal white matter, but can also be found in every lobe and in the brainstem (Calderón-Garcidueñas et al., 2013).

Clinically healthy children from MC selected by stringent criteria including the absence of known risk factors for cognitive or neurological deficits, exhibited structural, neurophysiological and cognitive detrimental effects compared to matched SES, gender, age and mother's IQ low pollution exposed children (Calderón-Garcidueñas et al., 2008, 2011a). The cognitive deficits in MC children matched the MRI volumetric changes in their right parietal and bilateral temporal areas (Calderón-Garcidueñas et al., 2012b).

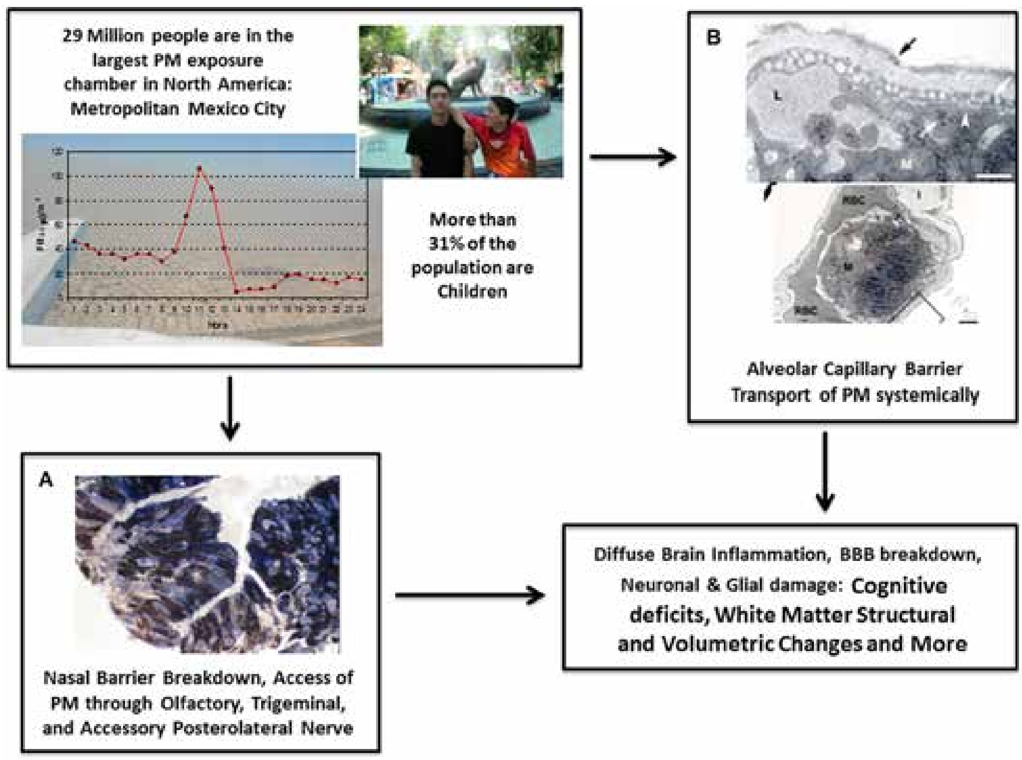

FIGURE 1 | Main mechanisms involved in brain damage associated with PM include the breakdown of nasal and olfactory pathways (A) and the alveolo-capillary pathway (B). All critical stages and effects of the biological pathways linked with **(A)** and **(B)** are shown in **Figure 2**. Through these pathways, PM produces systemic inflammation and travels around the body to ultimately cause pathological alterations including neuroinflammation, breakdown of the BBB, neuronal and glial damage, changes in white matter structure and volume, decline in cognitive abilities, auditory and vestibular impairment, and further deficits. **(A)** Nasal biopsy of 10 year-old Mexico City (MC) boy showing fine PM in the cytoplasm of epithelial cells stained with 1 μm toluidine blue. **(B)** Passage of PM through the alveolar capillary barrier in a Metropolitan MC young resident.

Complex modulation of cytokines and chemokines influences children's CNS structural and volumetric responses and cognitive correlates resulting from environmental pollution exposures. MC children performed more poorly across a variety of cognitive tests in comparison to the control (Calderón-Garcidueñas et al., 2008, 2011a,b).

A number of abnormalities within the auditory brainstem nuclei have been identified in children exposed to severe air pollution. Specifically, the neuronal cell bodies within the medial superior olive (MSO) are significantly smaller and more round than those in age-matched control brains (Calderón-Garcidueñas et al., 2011b). This finding is important because the MSO has clear roles in localization of sound sources, encoding temporal features of sound and likely plays an important role in brainstem encoding of speech. Integrity of the auditory brainstem nuclei can be accessed through a number of noninvasive techniques, such as brainstem auditory evoked potentials (BAEPs), otoacoustic emissions, speech recognition tasks and listening in background noise. Incidentally, similar morphological alterations were observed in autistic children (Kulesza and Mangunay, 2008; Kulesza et al., 2011) and correlated with abnormal brainstem reflexes (Lukose et al., 2013). Urban children have delayed central conduction time of brainstem neural transmission, resulting in increased risks for auditory and vestibular impairments and altered speech recognition abilities (Calderón-Garcidueñas et al., 2011b).

Based on the described evidence, it is reasonable to argue that air pollution exposed children experience a chronic, intense state of oxidative stress and exhibit an early brain imbalance in genes involved in inflammation, innate and adaptive immune responses, cell proliferation, necrosis and apoptosis (Calderón-Garcidueñas et al., 2012a, 2013). Neuroinflammation, endothelial activation, the significant heterogeneity of endothelial cells in CNS microvessels, and the BBB breakdown contribute to cognitive impairments, pathogenesis and pathophysiology of neurodegenerative states (Jian et al., 2012; Roher et al., 2012; Paul et al., 2013).

CHILDREN'S OUTCOMES ASSOCIATED WITH THE IMPACT OF AIR POLLUTION

The associations between cognition and urban pollution have been established in cities like Boston, where black carbon, a marker for traffic PM, predicted decreased cognitive function across assessments of verbal and nonverbal intelligence and memory in 9 year-olds (Suglia et al., 2008). Although genetic factors play a key role in CNS responses (as evidenced by the

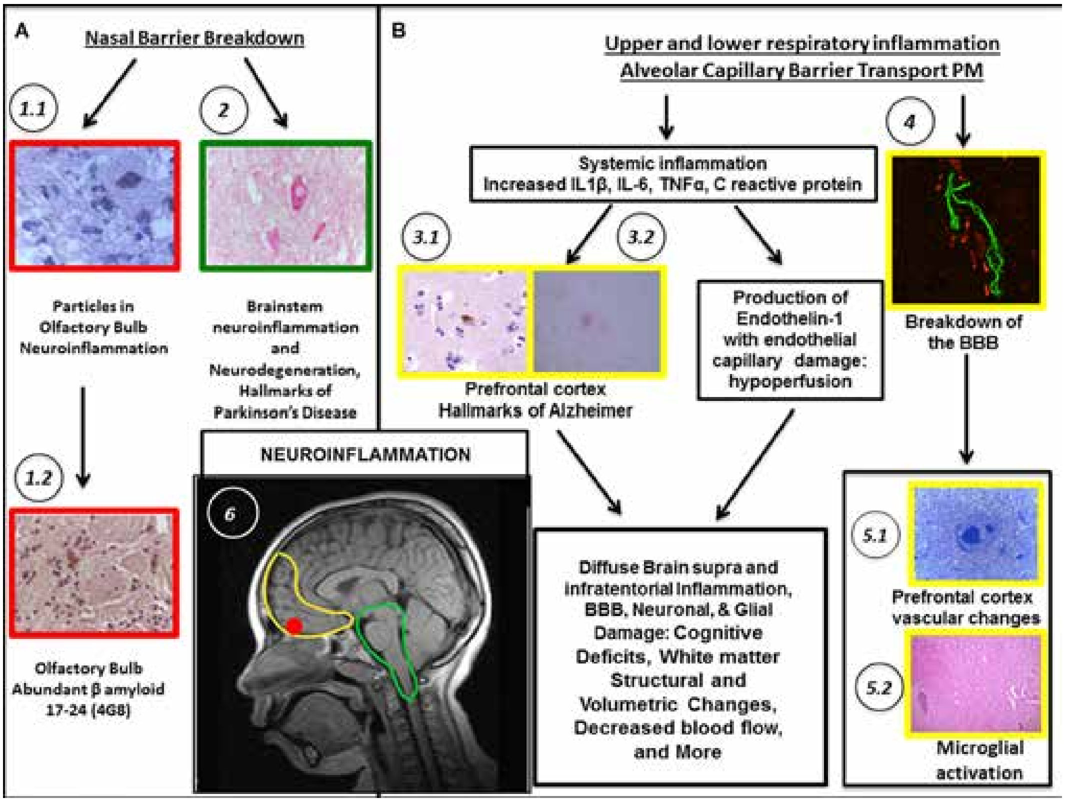

FIGURE 2 | Biological pathways associating PM exposure with the breakdown of nasal and olfactory pathways (A) and upper/lower respiratory tract inflammation along the passage of PM through the alveolo-capillary barrier (B) are shown. Localization in the brain (see **B-6**) is coded by the color of the outline frames of the panels: Yellow = prefrontal cortex; Red = Olfactory bulb; Green = Brainstem; Black and Arrows = stages along the pathways. Neuroinflammation is the common denominator. In **(A)**, nasal breakdown allows PM to directly access the brain. **(A)** pathway shows accumulated PM particles in the olfactory bulb. **(A-1.1)** Fourteen year-old MC boy with abundant particulate material in neurons in the glomerular region. **(A-1.2)** Accumulation of beta β amyloid, a hallmark of Alzheimer's disease (AD). **(A-2)** Inflammation and degenerative changes are significant in the brainstem. For example, accumulation of α synuclein in dopaminergic pigmented neurons in an 11 year-old MC girl is a hallmark of Parkinson's disease. In **(B)**, the extensive respiratory tract inflammation and the passage of ultrafine PM through the alveolar capillary barrier allows PM to access the body resulting in systemic inflammation. The increased production of endothelin 1, a potent vasoconstrictor results in vasoconstriction and cerebral hypoperfusion. The BBB (see especially **B-4**) is damaged and triggering of autoimmune responses directly damages neural components. **(B-3.1)** Frontal cortex in a 15 year-old boy. Abnormal tau protein-a marker of AD- both in the neuronal body and in neurites. **(B-3.2)** Frontal cortex in a 17 year-old boy. A diffuse amyloid plaque –a marker of AD–(red product) is seen surrounded by glial cells. **(B-4)** Frontal white matter blood vessel in a 20 year-old MC male shows BBB breakdown. **(B-5.1)** Young 15 month-old MC dog, frontal white matter abnormal arteriole. **(B-5.2)** Entorhinal area perivascular inflammation in a 22 year-old female from MC. **(B-6)** Sagittal view of MRI of a male MC resident aged 10.

acceleration of neurodegenerative pathology in children carrying an APOE 4 allele), studies such as the abovementioned ones in Boston and others, sketch a complex scenario where air pollution and SES can influence neural development and cognition along with known factors such as psychosocial stress and poor nutrition, thereby influencing and determining mental health, academic achievements and overall life performance (Siddique et al., 2011; Becerra et al., 2013). It is critical to point out that although SES is an additive independent risk factor, in several of the studies conducted not only in megacities such as New York City, Beijing, Sao Paulo, Los Angeles, but also in smaller metropolitan areas including Boston, Cincinnati, and Barcelona that we have reviewed earlier (Newman et al., 2013; Amato et al., 2014; Barbieri et al., 2014; Liu and Lewis, 2014; Perera et al., 2014; Tang et al., 2014), the effects of *outdoor* air pollution on children's brain did not vary interactively with low SES. Thus, outdoor air pollution effects are not a concern for just underprivileged populations although the fact that belonging to the lower end of the socioeconomic spectrum is very likely to aggravate detrimental health effects.

Although the direct and indirect influences of air pollution on several developmental outcomes are not fully understood, psychiatrists, clinical psychologists and allied mental health and pediatric professionals have a critical role to play in identifying the potential associations between exposure and behavioral issues. There are several emerging trends of evidence suggesting that air pollution may be associated with an array of atypical neurocognitive and behavioral changes in children and teens which are of legitimate public health concern and call for prediction and prevention of early environmental health risk factors (Borges et al., 2011; Haynes et al., 2011; Liu, 2011; Liu and Lewis, 2014).

An intriguing association has been identified recently between autism spectrum disorder including attention deficit hyperactive disorders (ADHD) and particle air pollution (Larsson et al., 2009; Zhang et al., 2010; Siddique et al., 2011; Becerra et al., 2013; Volk et al., 2013). Risk factors related to PM include maternal second and third hand smoke exposure, residency during gestation at the highest quartile of exposure to traffic-related air pollution, condensation on windows (a proxy for low rate of ventilation in homes) and polyvinyl chloride (i.e., indoor airborne phthalates) flooring, especially in the bedroom of parents. Interestingly, airway symptoms of wheezing and physician-diagnosed asthma were also associated with autism spectrum disorder 5 years later (Larsson et al., 2009). Since these associations are linking autism and ADHD with environmental variables, they warrant wider knowledge translation by and among the developmental, behavioral and clinical researchers and practitioners.

There are now also a handful of studies examining the effects of psychosocial stress and air pollution together on asthma; some suggest they act synergistically, whereas others find a more complex interaction where the socioeconomic and environmental conditions co-modulate the respiratory outcomes (for a review see Wright, 2011). These studies and the evolving asthma literature that speaks to the interactions between disease activity, psychosocial stress, learning disabilities, cognition and air pollution (Caldera-Alvarado et al., 2013) are further evidence of the more complex interactions impacting the CNS and the need for a multidisciplinary approach in the management of developmental, behavioral and cognitive problems in children at risk.

The reviewed evidence of brain, neurocognitive and behavioral detrimental outcomes associated with air pollution, collectively suggests substantive effects that may have long-term clinical repercussions in terms of degenerative diseases (Calderón-Garcidueñas et al., 2013). Given the social and economic burden of accelerated aging in our society, whose far-reaching ramifications are simply incalculable (see National Institute of Aging, National Institutes of Health and World Health Organization, 2001), a multidisciplinary approach aiming at screening target school populations that are most at risk, would seem a rather cost-effective and most beneficial public health strategy. Strong support for the need of neurocognitive and behavioral screening in the targeted risk populations of children comes from a growing psychological and epidemiological literature suggesting evidence of suboptimal cognitive functioning across the developmental span in *clinically healthy children* (Calderón-Garcidueñas et al., 2012b; Guxens and Sunyer, 2012). Importantly, a significant proportion of urban schools are situated near major traffic-related air pollution sources (Amram et al., 2011), and cognitive outcomes may be partly associated with air pollution levels around schools (Mohai et al., 2011).

LIMITATIONS OF CURRENT RESEARCH AND FUTURE DIRECTIONS: NEED FOR A MULTIDISCIPLINARY APPROACH AND CHILDREN'S PUBLIC HEALTH PRIORITY AGENDA

Air pollution effects on the developing brain may vary along a continuum from minor, subtle subclinical deficits in cognitive functioning to significant cognitive deficits that are identified readily by parents and/or teachers. The detrimental effects may also worsen with the age of the child, thus selected neurocognitive tools ought to be useful for measuring longitudinal studies across educational backgrounds and predicting overlaps in the functional areas and tests affected. Complex cognitive responses that may be affected include: attention and short-term memory, information processing speed and executive function, verbal abstraction, and visuospatial and motor skills. Deficits in auditory and vestibular responses and sound localization could also be expected, along with olfaction deficits. Most of the neuroimaging studies already mentioned (specifically using techniques such as Electroencephalography/Event-Related Potentials, BAEPs, structural and functional Magnetic Resonance Imaging, and Magnetic Resonance Spectroscopy) conducted in clinical and preclinical settings have all been reported to show a gradient of effects. However, one area of limitation is our fragmentary knowledge behind the pathology and the mechanisms of neurodevelopmental and neurodegenerative disorders that are exhibiting overlapping expressions for several of the effects identified in this review. Future studies need to be designed so that this limitation can be overcome.

Consistent with these observations, the National Institute of Environmental Health Sciences/National Institute of Health panel on outdoor air pollution indicated cognitive and neuropsychological (and possibly neuroimaging) screenings of children as one of the priority for future research advocating a multidisciplinary collaborative approach wherein brain-related development testing would have a prominent role (Block et al., 2012).

It seems relatively straightforward that health professionals, behavioral scientists, psychologists and psychiatrists should each have a responsibility to address the particular issues associated with air pollution in the measure and modality in which the individuals are impacted. Furthermore, the diffuse nature of the neuroinflammation and the evolving neurodegenerative changes observed in exposed children obligates us not to rely on a single study or measure but rather to employ a weight of evidence approach incorporating current clinical, neurophysiological, radiological and epidemiological research as well as the results of animal exposure studies to a single pollutant/mixtures/or pollutant components. Inflammatory biomarkers play a key role in the identification of children with positive volumetric and cognitive responses to their lifelong pollutant exposures (Calderón-Garcidueñas et al., 2012b). Since neuroinflammation/vascular damage/neurodegeneration go hand in hand (Calderón-Garcidueñas et al., 2013), establishing the definition of inflammatory/endothelial dysfunction biomarkers regarding the association between brain growth and developmental behavioral as well as psychological outcomes are urgently needed.

If the evidence is so convincing, why do not we lower pollution standards instead of launching expensive public health initiatives? Based on the current evidence and history, it seems extremely improbable that a global issue such as air pollution reduction will find a prompt consensus on decisive policy action towards better standards and their execution. The evidence accumulated so far clearly indicates that the neurocognitive effects of air pollution are substantive, they are apparent across all populations (not just the disadvantaged ones), and most importantly, the observed neurocognitive impairments are potentially and clinically relevant as an early indicator of evolving neurodegenerative precursors. Our ultimate goal should be to protect severely exposed children in large urban areas through multidimensional interventions yielding both impact and reach (i.e., on cognitive/behavioral, family participation, and modifiable lifestyle factors such as diet and micronutrient supply). One beneficial and cost-effective strategy for achieving those objectives is to have air pollution brain effects as key public health targets, and monitor the pediatric populations that are most at risk through preventative screening programs.

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Demand-Controlled Ventilation Using CO_2 Sensors

Preventing energy losses from over-ventilation while maintaining indoor air quality

Executive Summary

Demand-controlled ventilation (DCV) using carbon dioxide (CO_2) sensing is a combination of two technologies: CO_2 sensors that monitor CO_2 levels in the air inside a building, and an air-handling system that uses data from the sensors to regulate the amount of ventilation air admitted. CO_2 sensors continually monitor the air in a conditioned space. Given a predictable activity level, such as might occur in an office, people will exhale CO_2 at a predictable level. Thus CO_2 production in the space will very closely track occupancy. Outside CO_2 levels are typically at low concentrations of around 400 to 450 ppm. Given these two characteristics of CO_2, an indoor CO_2 measurement can be used to measure and control the amount of outside air at a low CO_2 concentration that is being introduced to dilute the CO_2 generated by building occupants. The result is that ventilation rates can be measured and controlled to a specific cfm/person based on actual occupancy. This is in contrast to the traditional method of ventilating at a fixed rate regardless of occupancy.

Handheld CO_2 sensor with data logging.

Building codes require that a minimum amount of fresh air be provided to ensure adequate air quality. To comply, ventilation systems often operate at a fixed rate based on an assumed occupancy (e.g., 15 cfm per person multiplied by the maximum design occupancy). The result is there often is much more fresh air coming into buildings than is necessary. That air must be conditioned, resulting in higher energy consumption and costs than is necessary with appropriate ventilation. In humid climates, excess ventilation also can result in uncomfortable humidity and mold and mildew growth, making the indoor air quality (IAQ) worse rather than better.

A lack of adequate fresh air, on the other hand, can make building occupants drowsy and uncomfortable. To avoid the problems of too much or too little fresh air, the heating, ventilation, and air-conditioning (HVAC) system can use DCV to tailor the amount of ventilation air to the occupancy level. CO_2 sensors have emerged as the primary technology for monitoring occupancy and implementing DCV. Energy savings come from controlling ventilation based on actual occupancy versus whatever the original design assumed.

Application Domain

CO_2 sensors have been available for about 12 years. An estimated 60,000 CO_2 sensors are sold annually for ventilation control in buildings, and the market is growing. There is a potential for millions of sensors to be used, since any building that has fresh air ventilation requirements might potentially benefit from the technology.

CO_2-based DCV has the most energy savings potential in buildings where occupancy fluctuates during a 24-hour period, is unpredictable, and peaks at a high level—for example, office buildings, government facilities, retail stores and shopping malls, movie theaters, auditoriums, schools, entertainment clubs and nightclubs.

CO_2 sensors are considered a mature technology and are offered by all major HVAC equipment and controls companies. The technology is recognized in ASHRAE Standard 62, the International Mechanical

Code (which establishes minimum regulations for mechanical systems), and some state and local building codes. Although the first CO_2 sensors sold were expensive, unreliable, and difficult to keep calibrated, manufacturers say they have largely resolved those problems. The unit cost of sensors has dropped from $400 to $500 a few years ago to $200 to $250 (not including installation). As market penetration increases, prices are expected to fall further.

Several manufacturers produce CO_2 sensors for DCV. Most manufacturers of thermostats and economizers are integrating CO_2 sensors into their products, and major manufacturers of packaged rooftop HVAC systems offer factory-installed CO_2 sensors as an option.

Benefits

DCV saves energy by avoiding the heating, cooling, and dehumidification of more ventilation air than is needed. CO_2 sensors are the most widely accepted technology currently available for implementing DCV. Additional benefits of CO_2-based DCV include

- Improved IAQ—By increasing ventilation if CO_2 levels rise to an unacceptable level,
- Improved humidity control—In humid climates, DCV can prevent unnecessary influxes of humid outdoor air that makes occupants uncomfortable and encourages mold and mildew growth.

Estimated Savings

The potential of CO_2-based DCV for operational energy savings has been estimated in the literature at from $0.05 to more than $1 per square foot annually. The highest payback can be expected in high-density spaces in which occupancy is variable and unpredictable (e.g., auditoriums, some school buildings, meeting areas, and retail establishments), in locations with high heating and/or cooling demand, and in areas with high utility rates.

Design Considerations

CO_2 sensing is a fairly simple technology, and installation of the sensors themselves is not complicated. Including CO_2-based DCV in a new HVAC installation should not add significantly to the difficulty of commissioning the system. However, retrofitting an existing system for DCV may be more problematic, particularly for an older system with pneumatic controls. Applying a CO_2-based DCV strategy using ASHRAE 62 is more complicated than simply installing CO_2 sensors and using them to control dampers. In variable-air-volume systems, particularly, fairly complex calculations and control algorithms may be necessary to program the control system properly for DCV. The use of a more complex control algorithm often provides increased savings and improved IAQ; while it increases the level of commissioning, the results outweigh the extra initial time and expense.

Maintenance Impact

Maintenance of the sensors themselves is not generally reported to be a problem. Manufacturers offer sensors that recalibrate themselves automatically and that are guaranteed not to need calibration for up to 5 years. However, it is recommended that calibration be checked periodically by comparing sensor readings during a several-hour period when the building is unoccupied with readings from the outdoor air. Many sensor models are able to sense calibration problems and alert maintenance personnel if they are malfunctioning.

Costs

Costs for sensors have dropped by about 50% over the last several years. Sensors typically cost about $250 to $260 each, uninstalled. For a new system, the installed cost will generally be about $600 to $700 per zone. For a retrofit system, the cost will depend on what type of control system the building has. A controls contractor estimates installed costs for retrofit applications at from $700 to $900 per zone for systems with an existing DDC programmable controller and from $900 to $1200 per zone for systems with pneumatic, electronic, or application-specific DDCs. Installation costs for wireless systems are minimal beyond the cost of the actual sensor and gateway that can serve multiple sensor units.

In addition to the installation of the sensors, other components such as variable frequency drives and control input and output hardware often are needed to control the whole building, incrementally increasing the overall installed project cost beyond just the sensor installation cost.

Contents

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Abstract

Demand-controlled ventilation (DCV) using carbon dioxide (CO_2) sensors combines two technologies: advanced gas sensing and an air-handling system that uses data from the sensors to regulate ventilation. CO_2 sensors continually monitor the air in a conditioned space. Since people exhale CO_2, the difference between the indoor CO_2 concentration and the level outside the building indicates the occupancy and/or activity level in a space and thus its ventilation requirements. The sensors send CO_2 readings to the ventilation controls, which automatically increase ventilation when CO_2 concentrations in a zone rise above a specified level.

Either too little or too much fresh air in a building can be a problem. Over-ventilation results in higher energy usage and costs than are necessary with appropriate ventilation while potentially increasing IAQ problems in warm, humid climates. Inadequate ventilation leads to poor air quality that can cause occupant discomfort and health problems. To ensure adequate air quality in buildings, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) recommended a ventilation rate of 15–20 cfm per person in ASHRAE Standard 62-1999. To meet the standard, many ventilation systems are designed to admit air at the maximum level whenever a building is occupied, as if every area were always at full occupancy. The result, in many cases, has been buildings that are highly over-ventilated. The development of CO_2-based DVC was driven in part by the need to satisfy ASHRAE 62 without overventilating.

Non-dispersive infrared CO_2 sensors are the type most widely used. All major makers of heating, ventilation, and air-conditioning (HVAC) equipment and HVAC controls offer the sensors, either as separate units or as a part of packaged HVAC systems. Although earlier sensors were plagued by reliability and calibration problems, those issues seem to have been largely resolved in newer models.

Typically, a CO_2 sensor is installed on the wall like a thermostat. Newer products entering the market combine thermostats and CO_2 and relative humidity sensors, the three primary indicators of human comfort, in one unit. Sensors may be installed inside ductwork rather than wall-mounted, but in-duct installation is not recommended for all applications. In a conventional "wired" CO_2 sensor system, wires are run from the sensors to the HVAC controls or to the damper actuators. With wireless CO_2 sensors, the data are transmitted to the building automation system via a wireless gateway for use in the control algorithm. Properly functioning modulating dampers are necessary. Pneumatic controls may need to be replaced with electronic or direct digital controls. In a retrofit installation, dampers may need to be repaired or upgraded to work with the sensors.

In all applications of CO_2-based DCV, a minimum base ventilation rate must be provided at all times the building is occupied. A higher rate may be needed for buildings in which building materials, contents, or processes release chemicals into the air. DCV should be used only in areas where human activity is the main reason for ventilating the space. Industrial or laboratory spaces are unsuitable for CO_2-based ventilation control.

The potential of CO_2-based DCV for energy savings is estimated at from $0.05 to more than $1 per square foot annually. The highest payback can be expected in high-density spaces in which occupancy is variable and unpredictable (e.g., auditoriums, some school buildings, meeting areas, and retail establishments), in locations with high heating and/or cooling demand, and in areas with high utility rates. Case studies show DCV offers greater savings for heating than for cooling. In areas where peak power demand and peak prices are an issue, DCV can be used to control loads in response to real-time prices. In those locations, DCV may enable significant cost savings even with little or no energy savings.

CO_2-based DCV does not interfere with economizers or other systems that introduce outdoor air into a building for cooling. Economizer operation overrides DCV when conditions warrant economizer use. Buildings that use evaporative cooling may not benefit from DCV during the cooling season.

Costs for sensors have dropped by about 50% over the last several years as the technology has matured and become more widely used. Sensors typically cost about $250 to $260 each, uninstalled. For a new system, the installed cost will generally be about $600 to $700 per zone. For a retrofit system, the cost will depend on what type of control system the building has and the degree of difficulty of installing signal and power wiring for a wired system. A complete wireless sensor system can be deployed quickly and without additional cost as such systems are battery powered. Given the advances in battery technology and microprocessor-controlled power management, sensors can be expected to operate for 2–3 years before they require a battery change.

About the Technology

Demand-controlled ventilation (DCV) using carbon dioxide (CO_2) sensing is a combination of two technologies: CO_2 sensors that monitor the levels of CO_2 in the air inside a building, and an air-handling system that uses data from the sensors to regulate the amount of outside air admitted for ventilation. DCV operates on the premise that basing the amount of ventilation air on the fluctuating needs of building occupants, rather than on a pre-set, fixed formula, will save energy and at the same time help maintain indoor air quality (IAQ) at healthy levels.

CO_2 sensors continually monitor the air in a conditioned space. Because people constantly exhale CO_2, the difference between the indoor CO_2 concentration and the level outside the building indicates the occupancy and/or activity level in a space and thus its ventilation requirements. (An indoor/

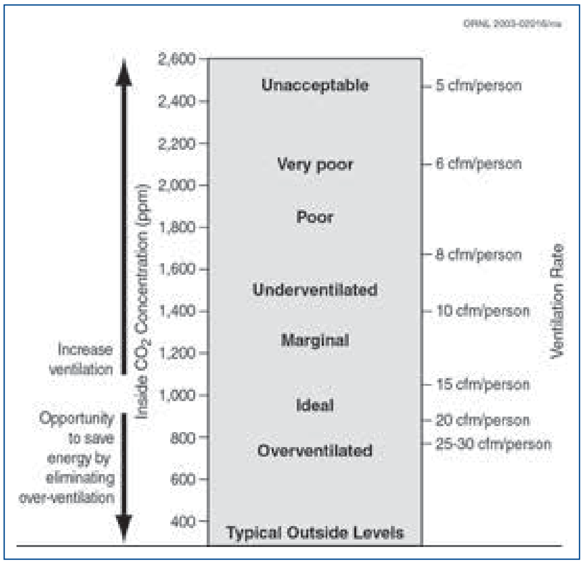


Figure 1. The relationship between CO_2 and ventilation rates, assuming office-type activity.

outdoor CO_2 differential of 700 ppm is usually assumed to indicate a ventilation rate of 15 cfm/person; a differential of 500 ppm, a 20 cfm/person ventilation rate, etc.) The sensors send CO_2 readings to the air handling system, which automatically increases ventilation when CO_2 concentrations in a zone rise above a specified level.

Building codes specify that a minimum amount of fresh air be brought into a building to provide for adequate air quality. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) recommends a ventilation rate of 15-20 cfm per person in ASHRAE Standard 62.[1] To comply with codes, building ventilation systems often operate at constant or predetermined rates regardless of the occupancy level of the building. Many systems ventilate buildings at the maximum level all the time, as if every area were always fully occupied. Others are programmed to accommodate expected occupancy, varying the ventilation rate by time of day but without regard to the actual occupancy level. The result often is more ventilation air coming into buildings than is necessary. That air must be heated, cooled, or dehumidified/humidified, resulting in higher energy consumption and costs than would be necessary with appropriate ventilation. In addition, in humid climates, an overload of fresh air can result in uncomfortable humidity and mold and mildew growth, making the indoor air quality worse rather than better.

A lack of adequate fresh air, on the other hand, can make building occupants drowsy and uncomfortable as occupancy-related contaminants accumulate. A CO_2 level of around 1100 ppm (a differential of 700 ppm, assuming the outdoor air CO_2 level is around 400 ppm) indicates that the ventilation rate has dropped below acceptable levels and that contaminants in the air are increasing.

To avoid the problems of too much or too little fresh air, a heating, ventilation, and air-conditioning (HVAC) system can employ DCV to adjust the amount of ventilation air supplied to an indoor space according to the occupancy level. CO_2 sensors have emerged as the primary technology for monitoring occupancy and implementing DCV.

Application Domain

CO_2 sensors have been available for about 12 years. An estimated 60,000 CO_2 sensors are sold annually for ventilation control in buildings, and a manufacturer estimates the market is growing at about 40 to 60% per year. There is a potential for millions of sensors to be used, since any building that has fresh air ventilation requirements could potentially benefit from this refined control technology.

DCV using CO_2 sensors has the most energy-saving potential in buildings where occupancy fluctuates during a 24-hour period, is unpredictable, and peaks at a high level, for example, office buildings, government facilities, retail stores and shopping malls, movie theatres, auditoriums, schools, entertainment clubs and nightclubs. In buildings with more stable occupancy levels, DCV can ensure that the target ventilation rate per person is being provided at all times. DCV is more likely to reduce energy costs in areas with high utility rates or climate extremes.

CO_2-based DCV can operate in conjunction with economizers or other systems that introduce outdoor air into a building for heating or cooling. However, energy savings may be less where economizers are in use, depending on climate, occupancy schedule, and building type.

Buildings that use evaporative cooling may not benefit from DCV during the cooling season, and those that use heat exchangers to transfer heat between incoming and outgoing air may not realize significant energy savings.

In the next revision of its building code, California will begin requiring CO_2-based DCV in all buildings housing 25 people or more per 1000 ft^2. A proposed change in the Oregon building code would require DCV for HVAC systems with ventilation air requirements of at least 1500 cfm, serving areas with an occupant factor of 20 or less. ASHRAE 90 requires CO_2 sensors for DCV in high-density applications. The U.S. Green Building Code gives points in its Leadership in Energy and Environmental Design (LEED) rating system for use of CO_2-based ventilation control in buildings.

CO_2 sensors are considered a mature technology and are offered by all major HVAC equipment and controls companies. The technology is recognized in ASHRAE Standard 62, the International Mechanical Code (which establishes minimum regulations for mechanical systems), and some state and local building codes. The first CO_2 sensors sold were expensive, unreliable, and

[1] An ASHRAE standard is usually designated by a standard number and the year in which it was last revised. Standard 62 is under continuous maintenance and is constantly being revised.

difficult to keep calibrated accurately. However, manufacturers say they have largely resolved those problems-the units currently available generally are self-calibrating and similar to thermostats in price and reliability. A few years ago, sensors cost around $400 to $500 each; the cost now is usually about $200 to $250 per sensor (not including installation). As market penetration increases, sensor prices are expected to fall further.

Several manufacturers produce CO_2 sensors for use in DCV. Most manufacturers of thermostats and economizers are integrating CO_2 sensors into their products, and major manufacturers of packaged rooftop HVAC systems offer factory-installed CO_2 sensors as an option.

CO_2-based DCV is suitable only when there is a means of automatically adjusting the ventilation air supply (e.g., variable-speed fans or some variable damper arrangement). If this control is not presently available, the savings from DCV may justify the modifications to accommodate this degree of control.

CO_2 sensors designed for DCV are suitable only for controlling occupant-related ventilation. DCV does not eliminate the need for a base rate of ventilation to prevent degradation of air quality from contaminant sources unrelated to building occupancy, such as emissions from building materials. Thus CO_2-based DCV may not be appropriate—or may require higher target ventilation settings-in new buildings or others where there are contaminants not related to human occupancy, as it may not provide sufficient fresh air to dilute those contaminants. The CO_2 sensors used for DCV are not appropriate to monitor CO_2 for medical or industrial purposes that demand precise air quality control.

DCV should be used only in areas where human activity is the main reason for ventilating the space. Industrial or laboratory spaces that are subject to indoor air quality (IAQ) degradation from a wide variety of sources are unsuitable for CO_2-based ventilation control.

Energy-Saving Mechanism

The energy savings from CO_2 sensors for DCV result from the avoidance of heating, cooling, and dehumidifying fresh air in excess of what is needed to provide recommended ventilation rates. Many HVAC systems ventilate at a constant fixed level, usually the level prescribed for full occupancy, and thus provide more fresh air per occupant than the designed ventilation rate much of the time. Moreover, systems using fixed ventilation rates cannot accurately account for unanticipated air infiltration into a building (e.g., from leakage or opened windows) and adjust the fresh air intake accordingly.

DCV based on CO_2 sensing allows real-time control of the ventilation levels according to building occupancy. If a building is only 50% full, then only 50% of the design-rate ventilation air, not 100%, is pulled in. CO_2 sensors are the most widely accepted technology currently available for implementing DCV. They do this by increasing the ventilation rate whenever the CO_2 level in a space reaches a predetermined level that represents a differential between the indoor and outdoor CO_2 levels. The outdoor CO_2 level is slightly dependent on local conditions and elevation, but can generally be assumed to be around 400 ppm. An indoor level of 1100 ppm of CO_2 thus represents a 700-ppm differential and indicates a ventilation rate of 15 cfm per person in the occupied space. A differential of 500 ppm in the same space would indicate a ventilation rate of 20 cfm per person.

The technology most often used in CO_2 sensors is non-dispersive infrared spectroscopy. It is based on the principle that every gas absorbs light at specific wavelengths. Carbon dioxide sensors calculate CO_2 concentrations by measuring the absorption of infrared light (at a wavelength of 4.26 microns) by CO_2 molecules. The sensor apparatus incorporates a source of infrared radiation, a detector, and electronics to detect the absorption. Air from the area being monitored diffuses into a chamber

Figure 2. Typical non-dispersive infrared spectroscopic CO_2 sensor.

that has a light source at one end and a light detector at the other. Selective optical fibers mounted over the light detector permit only light at the 4.26-micron wavelength absorbed by CO_2 to pass through to the detector. As CO_2 levels rise, more infrared light is absorbed and less light is detectable.

Photo-acoustic CO_2 sensors also are available. In these sensors, also, air diffuses into a chamber in the sensors and is exposed to light at the wavelength absorbed by CO_2. As the CO_2 molecules absorb light energy, they heat the air chamber and causes pressure pulses. A piezo-resistor senses the pulses and transmits data to a processor that calculates the CO_2 level.

Electrochemical sensors measure the current transmitted across a gap filled with an electrochemical solution. CO_2 decreases the pH of the solution, freeing conductive metal ions. A weak electrical current can then flow across the gap; the current signals an increase in the CO_2 level.

Mixed-gas sensors also can detect CO_2 along with other gases in the air, but they have not proved to be effective for DCV because they do not measure CO_2 specifically and cannot be tied to ventilation rates as explicitly as a CO_2 sensor can.

Sensors generally are either wall-mounted in the space to be monitored or mounted inside the duct system. (Wall-mounted sensors usually are recommended because duct-mounted units provide data on the average CO_2 concentration in multiple spaces rather than on the CO_2 levels in individual areas.)

The sensors monitor CO_2 concentrations continually and send data to the system for controlling the ventilation equipment. Various types of control systems can be used to incorporate CO_2 sensing: simple setpoint control that activates a fan or damper when CO_2 levels exceed a setpoint; proportional control, in which sensor data adjust ventilation air volume through a range of levels; proportional-integral control, in which fresh air intake is controlled not only by the CO_2 level but also by the rate at which the level is changing; and two-stage controls for zone-based systems in which both temperature sensors and CO_2 sensors control ventilation.

Other Benefits

Potential secondary benefits of CO_2-based DCV include:

- Improved IAQ: By increasing the supply of fresh air to the building if CO_2 levels rise to an unacceptable level, the technology could prevent under-ventilation that results in poor air quality and stuffy rooms.
- Improved humidity control: In humid climates, DCV can prevent unnecessary influxes of humid outdoor air that causes occupants to be uncomfortable and encourages the growth of mold and mildew.
- Records of air quality data: Sensor readings can be logged to provide a reliable record of proper ventilation in a building. Such records can be useful in protecting building owners against ventilation-related illness or damage claims.
- Reduced operational running times for the major HVAC equipment: Improving the ability to condition the building could delay start-times of the HVAC equipment during morning pre-conditioning periods by as much as several hours on a Monday morning in humid climates, resulting in incremental energy and cost savings.

Variations

DCV can be implemented using methods other than CO_2 sensing to indicate occupancy levels or air quality conditions. For example, humidity sensors, motion detectors, particle counters, volatile organic contaminant sensors, and mixed-gas sensors can be used to regulate DCV. Time-controlled ventilation (e.g., using programmed time clocks) is also an option for buildings that are occupied only during certain times, for example, office buildings and schools. Based on a review of the literature, it appears that CO_2 sensors are becoming the industry standard for typical DCV applications.

CO_2 sensors are of three main types: infrared, electrochemical, and photo-acoustic. Based on the literature, infrared sensors appear to be the type most commonly used for DCV applications.

Combination sensing units are available that package wall-mounted CO_2 sensors with thermostats or with humidity sensors.

There are numerous variations in the types of HVAC systems and control systems with which CO_2-based DCV is implemented. CO_2-based DCV capability can be added to an existing system by installing sensors and connecting them with the air handling systems. Increasingly, new HVAC systems are being factory-equipped with input and controls strategies to accept CO_2-based DCV.

Installation

Typically, a CO_2 sensor is installed on the wall like a thermostat. Newer products entering the market combine thermostats and CO_2 and relative humidity sensors, the three primary indicators of human comfort, in one unit. Sensors may be installed inside ductwork instead of on a wall, but in-duct installation is not recommended for applications where the sensor would

All of these types of systems can be modified to accomplish a DCV strategy

Control Type	Minimum Modification	Recommended Modification
All	Apply ASHRAE Standard 62-1999 with CO_2 sensors provided in zones with high critical outside air (OA) calculations	Provide CO_2 sensors in all zones, using the highest zone to increase the fresh air provided by the associated air-handling unit (AHU)
Pneumatic	Provide electronic-to-pneumatic transducer to limit the OA damper position	Upgrade the AHU to DDC programmable control
Electronic	Provide electronic device to limit the OA damper position	Upgrade the AHU to DDC programmable control
DDC–application specific	Provide electronic device to limit the OA damper position	Upgrade the AHU to DDC programmable control
DDC-programmable	Modify the control program to provide new DCV strategy	Same as minimum

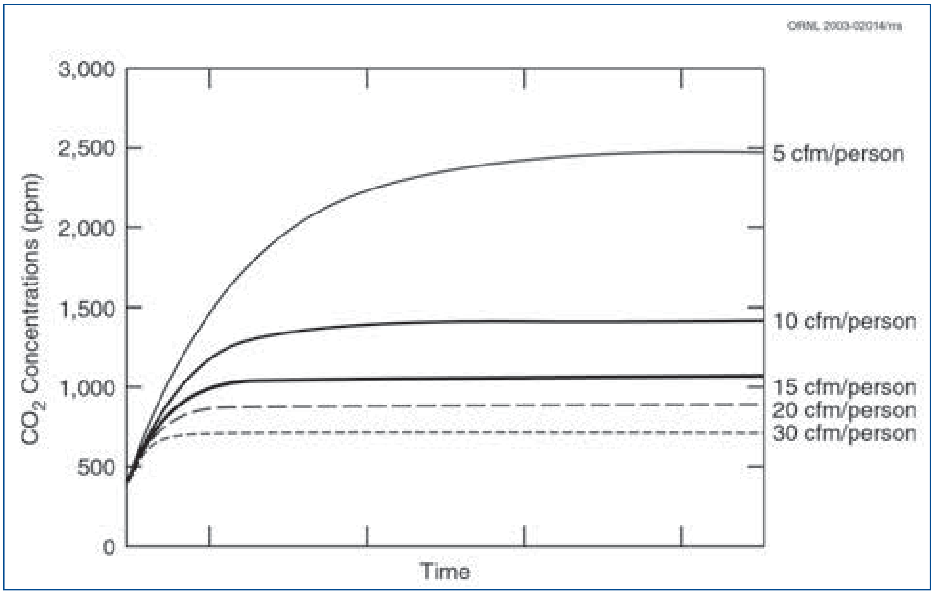


Figure 3. CO_2 equilibrium levels at various ventilation rates.

average readings from several different areas. With hardwired sensors (those requiring both power and signal wiring), wires are run from the sensors to the building's HVAC control system or to the actuator that controls the fresh air supply. Wireless sensors require neither power nor signal wiring, and the sensor data are fed into the HVAC controls via a gateway using one of several communication protocols.

In a building retrofit, dampers may need to be repaired or upgraded to work with the sensors. Properly functioning modulating dampers are necessary. Pneumatic controls will need to be replaced with electronic or direct digital controls (DDCs); it may also be worthwhile to replace existing electronic controls with DDCs. Actuator modules that do not have input points for the sensors will need to be upgraded.

Part of the preparation for implementing DCV is to monitor the air in the outdoor areas surrounding the building for at least a week to establish the CO_2 concentration in the ventilation air. The differential between the CO_2 levels of the outdoor and indoor air will determine the amount of fresh air needed to meet ventilation requirements. CO_2 concentrations in all zones inside the conditioned space also should be monitored for several days to indicate existing ventilation levels in the zones. This monitoring may identify problems with air-handling systems that need to be corrected before DCV is implemented.

To ensure that the sensors are correctly calibrated and working properly, a hand-held monitor should be used to check CO_2 concentrations inside the buildings regularly for a few days after the system begins operating. The readings from the monitor should be compared with the readings the sensors are sending to the ventilation system controls. Sensors that prove to be improperly calibrated should be recalibrated.

In all applications of CO_2-based DCV, a minimum ventilation rate should be provided at all times the building is occupied. A rate of 20–30% of the original design ventilation rate for the space at maximum occupancy is often recommended as a new baseline ventilation rate. A higher rate may be needed for buildings in which building materials, contents, or processes release chemicals into the air.

Federal-Sector Potential

Federal Technology Alerts target technologies that appear to have significant untapped federal-sector potential and for which some installation experience exists. CO_2 sensors are recognized as having potential to reduce energy consumption and costs resulting from over-ventilation of buildings while guarding against under-ventilation.

Estimated Savings and Market Potential

CO_2-sensors for demand-controlled ventilation are recognized as having potential to reduce energy consumption, costs, and emissions.

Demand-controlled ventilation has not been assessed by the New Technology Demonstration activities. There are no known estimates of the savings potential of CO_2-based DCV for the federal building sector. Therefore, this report cannot adequately quantify the energy-savings potential of the application of this technology for the federal sector.

The literature about DCV includes numerous estimates and models of the savings potential of DCV, as well as accounts of monitored savings in specific applications. The predicted and actual savings vary widely depending on climate, type of HVAC system with which DCV is implemented, occupancy patterns in the space in which is it implemented, and other operating conditions. The capability of the building staff to keep equipment adequately maintained and operating properly also may affect savings significantly.

The potential of CO_2-based DCV for operational energy savings has been estimated in some of the literature at from $0.05 to more than $1 per square foot annually. The highest payback can be expected in high-density spaces in which occupancy is variable and unpredictable (e.g., auditoriums, some school buildings, meeting areas, and retail establishments), in locations with high heating and/or cooling demand, and in areas with high utility rates.

A report by Lawrence Berkeley National Laboratory cited five case studies in large office buildings with CO_2-based DCV, all of which reported energy savings that resulted in payback times of from 0.4 to 2.2 years. Two of the studies were computer simulations. One of those, conducted in 1994, simulated a 10-floor office building located in Miami, Atlanta, Washington, D.C., New York, and Chicago. The simulation predicted large gas savings for heating and smaller electricity savings, resulting in predicted payback times for the different locations of from 1.4 to 2.2 years.

A 1999 study modeled the impact of DCV and economizer operation on energy use in four building types (office, retail, restaurant, school) in three locations representing different climates: Atlanta; Madison, Wisconsin; and Albuquerque. For cooling, predicted savings attributed to DCV depended greatly on location-savings were larger in Atlanta and Madison because humidity made economizer operation less beneficial. In low-humidity Albuquerque, economizer operation was much more significant than DCV in reducing cooling energy demand. In all three locations, DCV resulted in large savings in heating energy—27%, 38%, and 42% for the office building in Madison, Albuquerque, and Atlanta, respectively; from 70% in Madison to over 80% in Atlanta and Albuquerque for the school; and over 90% in all three locations for the retail and restaurant spaces. Similar results were obtained for 17 other U.S. locations modeled. In all locations, the office building showed the most modest savings.

A recent proposal for a change to the Oregon building code to require DCV in some applications cites a DOE2 analysis of implementing a DCV strategy in a middle school gymnasium. It predicts energy cost savings of $3700 per year from DCV and a simple payback of about 6 months.

No estimate of market potential for CO_2-based DCV in the federal sector was available.

Laboratory Perspective

Research on CO_2-based DCV at the national laboratories has been limited so far. The technology is generally regarded as a valid operational strategy that offers potential for energy and cost savings and protection of IAQ in many facilities. A study conducted by Lawrence Berkeley National Laboratory concludes that sensor-regulated DCV is generally cost-effective in buildings in which the measured parameter (e.g., CO_2) is the dominant emission, the occupancy schedule and levels are varied and unpredictable, and the heating/cooling requirements are large. Monitoring of CO_2-based DCV systems is under way at some national laboratories to quantify savings and analyze effects on IAQ.

Some caveats have emerged from laboratory experience. Calibration drift has been observed to be a problem in some sensors. The management of energy management systems so that they admit ventilation air at an appropriate CO_2 level is another. A researcher at Oak Ridge National Laboratory who works with building projects at federal facilities noted that a skilled, well-trained building maintenance staff is essential to proper functioning of the sensors and associated control systems. If other HVAC control systems in a building frequently function improperly, there probably will be problems with CO_2 sensors and DCV controls, also. He advises that a test installation be tried first to ensure that the building staff understand how the devices work, that the devices function properly, and that the staff can handle a larger DCV implementation.

Application

This section addresses technical aspects of applying the technology. The range of applications and climates in which the technology can be best applied are addressed. The advantages, limitations, and benefits in each application are enumerated. Design and integration concerns for the technology are discussed, including equipment and installation costs, installation details, maintenance impacts, and relevant codes and standards. Utility incentives and support are also discussed.

Application Screening

DCV based on CO_2 sensing offers the most potential energy savings in buildings where occupancy fluctuates during a 24-hour period, is somewhat unpredictable, and peaks at a high level. It is also more likely to reduce energy costs in locales that require heating and cooling for most of the year and where utility rates are high.

Savings opportunities are the greatest in buildings with low average occupancy levels compared with the design occupancy levels. Larger savings are likely in buildings that supply 100% outside air to conditioned spaces than in buildings that supply a mixture of outside and recirculated air.

Types of buildings in which CO_2-based DCV is likely to be cost-effective include large office buildings; assembly rooms, auditoriums, and lecture halls; large retail buildings and shopping malls; movie theaters; restaurants, bars and nightclubs; banks; outpatient areas in hospital; and hotel atriums or lobbies.

In primary and secondary schools, where occupancy is variable but predictable, time-controlled DCV may be more

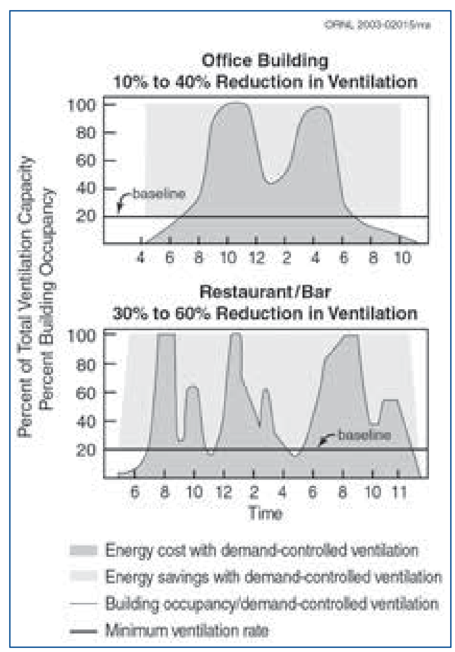


Figure 4. Percent of total ventilation capacity percent building occupancy.

cost-effective. College classroom buildings and large lecture rooms with variable occupancy through the day and the week are more appropriate candidates.

CO_2-based DCV does not interfere with economizers or other systems that introduce outdoor air into a building for cooling. Economizer operation overrides DCV when conditions warrant economizer use. The energy and cost savings for such arrangements depend on climate, occupancy schedule, and building type. Warm, humid climates (e.g., the Southeast) offer the most potential to save cooling energy with DCV because high humidity reduces opportunities for economizer cooling. In dry climates such as the desert Southwest, economizer operation may save more cooling energy than DCV. Additional cooling savings from DCV may be insignificant in such climates, and DCV without economizer cooling may even result in an energy penalty.

Buildings that use evaporative cooling may not benefit from DCV during the cooling season.

Case studies generally show greater savings for heating than for cooling in all climates. Heating savings are greatest where heating the ventilation air accounts for a large portion of the energy demand. A building with exchangers to transfer heat between incoming and exhaust air has less potential for savings from DCV because the heat exchangers reduce the energy penalty of ventilation air.

In areas where peak power demand and peak prices are an issue, DCV can be used to control loads in response to real-time prices. In those locations, DCV may enable significant cost savings even with little or no energy savings.

DCV can be implemented only in buildings in which the outside air supply can be automatically adjusted. If the air-handling system lacks that capability, it must be upgraded before CO_2-based DCV can be implemented. It is recommended that pneumatic controls be replaced with electronic or digital controls to implement CO_2-based DCV.

The cost of installing CO_2 sensors for DCV depends on how easily the existing control system can incorporate them. If the existing system has digital controls and available input points on the control modules for wired sensors, costs will be lower and implementation easier. Wireless sensors may be more easily integrated into an existing control system, as no new input control modules are needed.

Modeling is recommended, if feasible, to estimate the energy savings and cost-effectiveness of DCV in a specific situation.

CO_2 from human respiration must be the dominant pollutant in a space for CO_2-based DCV to be appropriate. Otherwise, it could lead to insufficient ventilation. Occupancy-based DCV is inappropriate for spaces with high levels of contaminants unrelated to human occupancy, including industrial or laboratory spaces. If CO_2-based DCV is used in a new building or other space containing materials that release irritating emissions (e.g., a clothing or carpet store), the target ventilation rate must be high enough to ensure that emissions are adequately diluted.

An HVAC system with CO_2-based DCV needs to be capable of a daily pre-occupancy (e.g., early morning) purge of inside air to avoid exposing occupants to emissions (e.g., from building materials) that accumulate while ventilation is at a low level.

Although DCV was developed mainly as an energy-efficiency technology, it also is useful to ensure acceptable IAQ. In a properly operating system, CO_2-based DCV ensures that the target ventilation rate per person is being provided at all times. Thus it may be appropriate for spaces where there are IAQ concerns. It may also help control the growth of mold and mildew by reducing unnecessarily large influxes of humid outdoor air.

Where to Apply

- Buildings where occupancy fluctuates during a 24-hour period, is somewhat unpredictable, and peaks at a high level.
- Locales that require heating and cooling for most of the year.
- Areas where utility rates are high.
- Areas where peak power demand and prices are high.
- Buildings with low average occupancy compared with the design occupancy.
- Large office buildings; assembly rooms, auditoriums, and lecture halls; large retail buildings and shopping malls; movie theaters; restaurants, bars and nightclubs; banks; outpatient areas in hospital; and hotel atriums or lobbies.
- Warm, humid climates.
- Buildings in which heating/cooling/dehumidifying the ventilation air accounts for a large portion of the energy demand.
- Buildings in which the outside air supply can be automatically adjusted.
- Buildings with HVAC systems that have, or can be upgraded to, electronic or digital controls.
- Spaces in which CO_2 from human respiration is the only or dominant pollutant.
- Spaces that do not have high levels of contaminants unrelated to human occupancy (e.g., industrial or laboratory spaces).
- Buildings in which poor IAQ resulting from under-ventilation or excessive humidity resulting from under- or over-ventilation is a concern.

Precautions

The following precautions should be kept in mind in considering the use of CO_2-based DCV.

- Sensors should be placed where they will provide readings that are close to actual conditions in the spaced to be controlled.
- Wall-mounted sensors are generally preferable to duct-mounted sensors.

- Sensors should not be mounted in locations where people will regularly breathe directly on them (e.g., at standing level near the coffee machine).
- Don't buy carelessly—choose sensors with a reputation for performing well in terms of self-calibration, drift, accuracy, and reliability.
- A competent, well-trained maintenance staff is important to a successful implementation.
- In a retrofit, it is important to make a thorough study of the HVAC system and troubleshoot for existing ventilation problems before installing a DCV system.
- A new base ventilation rate should be provided at any time the building is occupied. An often-cited guideline is 20 to 30% of the original design rate.
- Applications in moderate climates, especially where economizer operation contributes substantially to cooling, may show little energy/cost savings.
- Spaces where there are high levels of contaminants not related to occupancy may demand a higher ventilation rate than would be provided by DCV based solely on CO_2 levels.
- During the first year or so in a new building, it is advisable to maintain a higher ventilation rate than CO_2 sensing would indicate to ensure proper dilution of emissions from new materials.

Design Considerations

CO_2 sensing is a fairly simple technology, and installation of the sensors themselves is not complicated. Sensor voltage, power, and control output requirements are similar to those used commonly by thermostats. For wired sensor installations, the type of wire used for the signal wiring is often critical; some controls manufacturers specify the wire gauge, type, and shielding/grounding requirements to prevent signal irregularities and errors. With wireless sensors, these considerations are not a concern, as data are transmitted over a Federal Communications Commission-approved frequency. The wireless sensors are self-powered and use on-board power management to alert the building operator when the battery needs to be changed.

Most HVAC equipment suppliers are now offering systems designed to accommodate DCV and accept readings from CO_2 sensors, so including CO_2-based DCV in a new HVAC installation should not add significantly to the difficulty of getting the system into operation. However, retrofitting an existing system to work with DCV may be more problematic, particularly for an older system with pneumatic controls.

The sensors typically are mounted on walls like thermostats. Some manufacturers offer thermostat/sensor combinations. Units that monitor temperature, CO_2, and humidity are also available; they are useful with systems that include desiccant dehumidification to control the humidity load in ventilation air.

Data from the sensors are fed to the building's HVAC control system or to an actuator that controls the amount of ventilation air that is admitted. In a retrofit installation, it may be necessary to repair or upgrade dampers so they will work in a more dynamic, modulating fashion in response to the sensors. Properly functioning dampers that can be automatically controlled are essential. Pneumatic controls will need to be replaced with electronic controls or DDCs; it may also be worthwhile to replace existing electronic controls with DDCs. Actuator modules that do not have input points for the sensors will need to be upgraded to add input points.

Air handler unit and variable-air-volume controls are used for communication between the sensors and the air-handling system.

Control Type	Control Medium	Sequence
Pneumatic	Air pressure from 3 to 15 psi	Hard-piped: changes require additional hardware and physical modifications to the control air tubing
Electronic	Electronic signals from 2 to 10 V DC, 0 to 10 V DC, 4 to 20 mA are the most common. Other signals are 3 to 9 V DC, 6 to 9 V DC, 0 to 20 V phase cut	Hard-wired: changes require additional hardware and physical modifications to the control wiring
Direct digital control (DDC)—application-specific	Electronic signals from 2 to 10 V DC, 0 to 10 V DC, 4 to 20 mA are the most common. Other signals are 3 to 9 V DC, 6 to 9 V DC, 0 to 20 V phase cut, and via wireless transmission to multi-protocol enabled gateways	Programmed into an electronic controller that can be configured: some systems may need additional hardware to accomplish desired sequences
DDC—programmable	Electronic signals from 2 to 10 V DC, 0 to 10 V DC, 4 to 20 mA are the most common. Other signals are 3 to 9 V DC, 6 to 9 V DC, 0 to 20 V phase cut and via wireless transmission to multi-protocol enabled gateways	Programmed into an electronic controller that can be reprogrammed to accomplish desired sequences

The application of a CO_2-based DCV strategy using ASHRAE 62 is more complicated than simply installing CO_2 sensors and using them to control dampers. In variable-air-volume systems, particularly, fairly complex calculations and control algorithms may be necessary to program the control system properly for DCV.

DCV is compatible with economizers or other systems that can bring outdoor air into a building for cooling. Economizer operation overrides DCV when conditions favor economizer use. DCV used in conjunction with an enthalpy economizer (one regulated by relative humidity) probably will save more energy than DCV with a temperature-regulated economizer.

Heat exchangers that transfer heat between supply air and exhaust air reduce the energy demand caused by large inflows of ventilation air; therefore, DCV may not reduce energy use in buildings with heat exchangers. Evaporative cooling systems may not benefit from DCV during the cooling season.

Maintenance Impact

Maintenance of the sensors themselves is not reported to be a problem. Although earlier sensor models had reliability problems, the literature generally reports that newer models typically are reliable and accurate. Manufacturers offer sensors that recalibrate themselves automatically and that are guaranteed not to need calibration for up to 5 years. However, it is recommended that calibration be checked periodically by comparing sensor readings during a several-hour period when the building is unoccupied with readings from the outdoor air. Many sensor models are able to sense calibration problems and alert maintenance personnel if they are malfunctioning.

Some users report problems in getting the sensors calibrated initially. A hand-held monitor should be used to ensure that the installed sensors are measuring CO_2 concentrations in their zones accurately.

CO_2-based DCV is a more sophisticated technology than many maintenance personnel are accustomed to, a building researcher noted. A facility with a well-trained staff who know how to maintain and troubleshoot controls is the best candidate for a CO_2-based DCV system.

Equipment Warranties

The prospective user should ask potential suppliers, contractors, and installers about warranties for specific equipment models. Warranties for CO_2 sensors vary widely among different manufacturers. Those reviewed offer warranty periods for parts and labor ranging from 90 days from the date of shipment to 5 years from the date of purchase. A warranty period of 12 to 18 months for parts and labor appears to be fairly common. Some sensors are guaranteed to remain calibrated for at least 5 years, and at least one manufacturer offers a lifetime calibration guarantee.

Codes and Standards

The use of CO_2-based DCV is accepted in both ASHRAE 62 and the International Mechanical Code (IMC). The IMC is referenced by the Building Officials and Code Administrators International, the Southern Building Code Congress International, and the International Code Conference of Building Officials, which together establish the model code language used in local and state building codes through the United States. The commentary on IMC Section 403.1 states, "The intent of this section is to allow the rate of ventilation to modulate in proportion to the number of occupants. CO_2 detectors can be used to sense the level of CO_2 concentrations which are indicative of the number of occupants... and this knowledge can be used to estimate the occupant load in a space."

ASHRAE 62 recommends DCV for all ventilation systems with design outside air capacities of greater than 3000 ft^3 per inch serving areas with an average design occupancy density of more than 100 people per 1000 ft^2.

The California Building Standards Code was amended in June 2001 to require CO_2-based DCV in some high-density applications during periods of partial occupancy. A proposed change to the Oregon Building Code (NR-HVAC-7) would require HVAC systems to include provision for DCV during periods when spaces are only partially occupied.

Costs

Costs for sensors have dropped by about 50% over the last several years as the technology has matured and become more widely used. Sensors typically cost about \$250 to \$260 each, uninstalled. For a new system, the installed cost will generally be about \$600 to \$700 per zone. For a retrofit system, the cost will depend on what type of control system the building has. A controls contractor estimates installed costs for retrofit applications at from \$700 to \$900 per zone for systems with an existing DDC programmable controller and from \$900 to \$1200 per zone for systems with pneumatic, electronic, or application-specific DDCs. Installation costs for wireless systems are minimal beyond the cost of the actual sensor and gateway that can serve multiple sensor units.

In addition to the installation of the sensors, other components such as variable frequency drives, control input and output hardware are often needed to control the whole building, incrementally increasing the overall installed project cost beyond just the sensor cost.

Utility Incentives and Support

No specific information was found regarding utility incentives that are in place for CO_2-based DCV. Some states (e.g., California) are considering such an incentive program. Most electric and natural gas utility companies have rebate programs to promote energy-efficiency technologies that result in overall improvement in building performance, and DCV systems would quality for incentives under some of those programs.

DCV is one of the technologies that utilities might consider for financial incentives in working with federal customers through a utility energy service contract on energy-efficiency projects at federal sites.

Technology Performance

Field Experience

Three building operators whose facilities have installed CO_2 sensors for DCV and a controls engineer whose company oversees HVAC installations were contacted for this report regarding their experience with the use of CO_2-based DCV. All were generally pleased with the performance they have observed, although one reported problems with getting the sensors properly calibrated and wired.

Purdue University has installed CO_2 sensors in 12 large auditoriums and lecture halls (100 to 500 seats) to address both air quality issues and energy costs. The sensors were added to existing air handling systems, and modulating outside damper actuators were added where they were not already in place. The existing air-handling units were 15 to 50 years old. Some of the rooms had pneumatic dampers with electronic controls; those controls were not replaced unless they were in bad condition. The large auditoriums had DDC systems. All the existing control modules had enough available inputs to add the sensors.

Purdue's controls systems engineer reported that there were minor problems with retrofitting the older air-handling systems, but they were the same kinds of problems that would have surfaced with a conventional HVAC retrofit-a lack of original or updated building plans and plans that did not match the existing systems. "We had to do some legwork to verify the existing configurations. It would be easier with new systems," she said.

Purdue has found the equipment installed to be reliable, and it has performed as expected. There has been a negligible impact on the maintenance staff because the sensors installed recalibrate themselves automatically. Purdue had previously installed sensors from another manufacturer that proved unsatisfactory because they could not be calibrated properly or could not maintain their calibration, the controls engineer said. "The calibration issue is very important in sensor selection," she said. The maintenance for the other equipment installed has been comparable to maintenance on the systems replaced.

Once the sensors began operating, they revealed that some of the lecture rooms had been underventilated by the old systems. The sensors worked well in resolving IAQ issues. Purdue has not monitored energy use since the sensors and new dampers were installed, but trended data have shown that the ventilation dampers modulate to lower or minimal positions when the lecture rooms are unoccupied or partly occupied and on weekends. Before the sensors were installed, the dampers were open to ventilate for full occupancy during the occupied cycle time (6 A.M. to 10 P.M. weekdays and 8 A.M. to 4 P.M. Saturdays).

Purdue continues to install CO_2-based DCV in new applications in large rooms with variable occupancy. It will be added in a renovation of the air handling system in a 900-person-capacity ballroom of the Purdue Memorial Union and is being reviewed for application in dining halls on campus.

A CO_2 sensor was installed in an office building on the Beaufort Marine Corps Air Station in South Carolina to regulate the makeup air system. It is the first of several DCV retrofits planned on the base as part of an energy services performance contract and a Marine Corps-funded controls system upgrade for the station. The air station is located in the low country of South Carolina, a particularly humid climate with a heavy cooling load.

The office building, a one-story 41,354 ft^2 facility with no windows, contains offices and a flight simulator. It was designed for 500 people, and the ventilation system supplied enough air to meet ASHRAE standards for 500, but the occupancy is rarely over 100, said Neil Tisdale, utilities director for the base. "That's a lot of air to be conditioning for no reason." The sensor was added as part of a makeup-air-system retrofit. The system already had modulating dampers and DDCs. Adding CO_2-based DCV was fairly simple—installing a sensor and modifying the control program to regulate the damper with input from the sensor. The CO_2 sensor was placed in the return air path.

The system has been operating for a year, Tisdale said, and he is not aware of any maintenance problems or malfunctions. He ventured a rough estimate that the DCV system reduces the cooling load for the building by 20 tons, saving roughly of 12 megawatt hours of power annually. The load for the building's chiller, sized to provide cool air for 500 people, was reduced so much that part of the chilled water was diverted and used to cool an adjacent 11,000 ft^2 building.

A large hospital in Houston, Texas, has installed CO_2 sensors in its auditoriums to ensure good IAQ and control energy costs, according to the hospital's manager of energy services. The sensors were added to existing systems, all of which had digital controls; integrating the sensors was not difficult, he said. The sensor input is not yet being used to control the dampers automatically; building staff are monitoring the sensors to see whether they will control air changes properly before switching to automatic control. "We're going to take it a step at a time and expand gradually," the energy services manager said. The switch to direct control of dampers by the sensors will take "minutes" to implement and will probably occur during the coming year, he said.

When the hospital begin installing the sensors, it was discovered that about half of them were not wired properly and needed to be rewired, he said. Many of the units were calibrated incorrectly and had to be recalibrated using a hand-held meter. "Some of them were showing 4000 to 5000 ppm of CO_2. You can't just set them up and assume they'll work properly," he cautioned.

However, he expects the sensors and DCV to perform well now that the initial problems have been addressed. They may be added in other areas such as busy foyers and other gathering areas once the conference room installation is in full operation.

The owner of a digital controls company who oversees HVAC installations says his company's clients who have installed CO_2-based DCV systems have been generally pleased with their performance and found DCV to be a valuable addition. A new HVAC installation that incorporates CO_2 sensors and DCV is of minimal cost and difficulty and requires only a few additional calculations to set up the air handling program properly, he said. He cautions that sensors should be installed to cover every CO_2 zone in an area because high occupancy, and a corresponding high CO_2 level, in one zone may not be reflected in the sensor readings from the adjacent zone.

Although his firm has not done formal studies of savings from DCV, it has seen a reduction in outside air requirements in all DCV installations because none of the facilities are at the design occupancy all the time. The largest energy savings are likely in buildings designed to meet ASHRAE 62 requirements, he said, because they are likely to be admitting more unneeded outside air.

He notes that if a building has previously been chronically under-ventilated, installing DCV might increase rather than decrease energy usage because it would bring in more outside air. However, DCV will correct IAQ problems and reduce liability for IAQ-related illnesses in such situations and may correct problems with mold growth.

The maintenance impact of installing CO_2 sensors is usually minimal if the sensors are self-calibrating, he said. Sensor calibration can be checked periodically by comparing indoor sensor readings with metered outside air readings after a building has been unoccupied for about 5 hours.

Energy Savings

None of the building operators interviewed had measured energy consumption before and after the installation of CO_2 sensors. However, both Purdue staff and the controls company owner have observed lower outside air requirements in facilities using DCV, which generally results in reduced energy demand.

Maintenance Impact

The maintenance impact of installing CO_2 sensors has been minimal at Purdue. The sensors used are self-calibrating and have performed reliably. The hospital in Texas reported problems with getting several of the sensors calibrated initially and had to use hand-held monitors to recalibrate them. In addition, some of the sensors were wired improperly and had to be corrected.

Case Study

This case study describes the methodology used to assess the cost and energy savings implications of retrofitting a building for CO_2-based ventilation control. This methodology can be applied to any building that has a track record of energy usage. In this case, the preliminary assessment of the building showed significant energy savings were available. The performance of the building after 6 months of operating with CO_2 control is also presented and shows that the predicted performance was slightly conservative compared with the actual savings realized.

Facility Description

This case study addresses a privately owned (non-government) 30-story Class A office building in Birmingham that was retrofitted with a CO_2-based ventilation control system in 2001. It had an existing state-of-the-art digital building control system installed several years earlier that was fully functional. The building was also upgraded to qualify for the EnergyStar label awarded by EPA to buildings having met qualifying energy efficiency standards.

Utility costs for the building were very low, $0.48/kWh during the base year of 1999; overall energy costs for the base year were $1.61 ft^2/year, representing 117,992 Btu/ft^2/year. This energy performance was compared with that of other similar buildings in that region using the DOE Energy Information Administration (EIA) energy intensity indices, which provide a general guide to average energy usage for different types of buildings in a region. The case study building was found to consume about 30% more than those found in the EIA indices. The fact that the energy cost was higher than average provided some preliminary indication that despite the low utility costs and EnergyStar rating, there were some opportunities for further energy conservation.

Of the total energy consumed by the building in the year 2000, 84.55% was spent on electricity for a total of 13,966,500 kWh or $670,742 annually; the maximum peak load was 3,318 kW. Of the remaining total energy consumed by the building, 13.81% was spent on steam for a total of 7,810,000 lb at a cost of $122,581 annually.

Existing Technology Description

The building HVAC system was designed with two air-handling units (AHUs) per floor, located on opposite sides of the building. Variable air volume (VAV) boxes served interior zones, and linear diffusers were located on perimeter zones. The linear diffusers have re-heat capability; the interior VAV boxes do not. Each AHU fan motor was controlled by a variable-frequency drive (VFD) to supply VAV boxes on the floor. Each AHU was on a time-of-day schedule provided by the automation system, wherein the units were scheduled on and off to correspond with the staff occupancy for that particular floor on a Monday through Friday basis, with limited Saturday hours of operation. Sunday was most often scheduled off all day for most floors. Because of the nature of the client operations, a few floors operated 24 hours per day, 7 days per week.

Outside air is drawn into each AHU at each floor through a ducted grille. The combined general building and bathroom exhaust are provided by twin fans (of differing sizes) exhausted at the roof level by connecting all floors through twin vertical shafts. Both exhaust fans were of a constant-speed design, exhausting the full design load air regardless of the intake of outside air into the building. Although a limited number of floors operated 24 hours per day, both exhaust fans ran constantly at the full design load. This feature probably also contributed to the higher than normal operating cost for the building.

The building had a DDC building air system that was deemed capable of executing a DCV strategy with some additional programming, and had sufficient input/output capacity to add the required components (e.g., CO_2 sensors, peripheral I/O modules).

New Technology Equipment Selection

The building automation system (BAS), an existing Siemens System 600, had been installed several years previously. It was deemed capable of accepting the data from the new CO_2 sensors, able to execute the new control strategy, and to have sufficient spare point capacity to provide the required input/output (I/O) from/to the new devices. Four new Telaire series 8002, dual-beam CO_2 sensors were installed per floor, except on the second floor, which had a number of enclosed meeting/conference rooms. One CO_2 sensor was installed in each of these rooms. One outside CO_2 sensor was installed to provide accurate indoor/outdoor CO_2 differential readings.To facilitate the additional I/O point requirements, new modules were installed within each S600 cabinet. For the CO_2 sensors, analog input modules accepting a 4-20 mA signal were needed, for the new fully proportional electric actuators, replacing the old relay (open/closed) actuators required analog modules driving a 0-10 V signal.

The existing building exhaust fans were retrofitted with Magnatek VFDs to balance the aggregate total of outside-air intake. The Magnatek VFDs were specified with factory-installed Siemens S600 FLN (field level network) cards to facilitate the connection to the S600 BAS without having to 'hardwire' each I/O point into the S600 control cabinet; this arrangement saved labor and the expense of individual I/O modules while simultaneously providing much more motor performance data to the building owner.

Completing the BAS component changes were the addition of one Setra building static pressure sensor that was essential to ensure a positive pressure in the whole building relative to the outside.

No other major control components were required for the case study building; however, the application of a new and fairly complex control strategy was essential to execute the DCV application. The DCV control algorithm is the most critical aspect of the project, as failure to implement an effective control sequence will yield lower energy savings performance.

Building Upgrade Assessment

Building owners must be able to evaluate the energy-saving potential and cost of specific initiatives to weigh the value of various building upgrade options. The methodology used to assess the potential of CO_2-based ventilation control involved five basic steps.

1. Spot measurement of CO_2 levels
2. Trend logging of CO_2 and other environmental factors
3. Estimation of the savings potential
4. Implementation assessment
5. Payback analysis

1. Spot measurement of CO_2

As indicated previously, CO_2 concentrations can be correlated to cfm/person ventilation rates inside a space. For a preliminary assessment of ventilation rates for this building, a number of spot measurements of CO_2 concentrations were made on each floor. A hand-held CO_2 monitor was used that is capable of calculating the cfm/person ventilation rate based on inside/outside differential CO_2 concentrations. The monitor assumes outside concentrations are 400 ppm, but it will also allow the baseline concentration to be set based on an actual outside measurement.

Spot measurements for CO_2 were made in the mid-morning to late morning and late afternoon hours on weekdays, after occupancy had stabilized in the building. They were taken while the building was not operating in economizer mode.

The results of the spot measurements showed that most areas of the building under study had CO_2 concentrations below 700-800 ppm, corresponding to ventilation rates in the range of 28 to 35 cfm/person. These rates were well over the original design target of 20 cfm/person. The chart shows the correlation between peak CO_2 levels

Figure 5. Handheld CO_2 sensor with cfm/person calculation and data logging.

and cfm/person ventilation rates, assuming office-type activity and an outside level of 400 ppm. Based on the spot measurements, it appeared that this building could be a good candidate for energy savings through better control of ventilation. These results warranted further investigation.

2. Trend logging of environmental factors

Trend logging was conducted over 7 typical days in the building to ensure that representative conditions were being measured. Ideally, measurements should be made in the major occupancy zones on each floor. If many locations are involved and monitoring devices are limited, multiple measurement sessions may be necessary. Devices used for measurement should measure CO_2 and should be able to log concentrations to a database every 15 minutes for a period of a week (at least 672 data points per parameter measured). Typically, data-logging sensors come with software to adjust, download and graph the results.

Several locations in the building were monitored over 7 days. Results of trend logging verified that the building was over-ventilated compared with the original design. The ventilation rate can be determined by looking at portions of the graph that show extended periods of operation where the CO_2 levels have stabilized; these indicate that the amount of CO_2 produced by people has reached equilibrium with the ventilation rate of the space. These periods are represented by the flat areas at the peak of each of the daily trend logs. In almost all locations, CO_2 levels and calculated ventilation rates were similar to those recorded during spot measurements. In general, peak levels around 930 ppm indicate a ventilation rate of 20 cfm/person; peak levels near 1100 ppm would indicate ventilation rates of 15 cfm/person. At the peak values recorded in the chart (674 ppm on average), the effective delivered amount of fresh air per person was more than 34 cfm/person, or 170% of the design need of 20 cfm/person. During periods of lower occupancy throughout the day and during Saturday morning operation, the effective delivered cfm/person considerably exceeded design needs and resulted in the use of excess energy to condition the surplus outside air.

Over-ventilation in the space may be due to either space densities being below original design conditions or the upward adjustment of outside air delivery to the building over design conditions. The building operator indicated that during summer months, occupants in the building often complained of uncomfortable humidity levels, indicating that perhaps the existing system was introducing more outside air than the system was originally designed for. This often happens when building operators "tweak" the building control system or air intakes to respond to complaints or to better tune the "feel" of the building. Based on hundreds of measurements in buildings throughout the country, over-ventilation appears to be a common problem in office buildings.

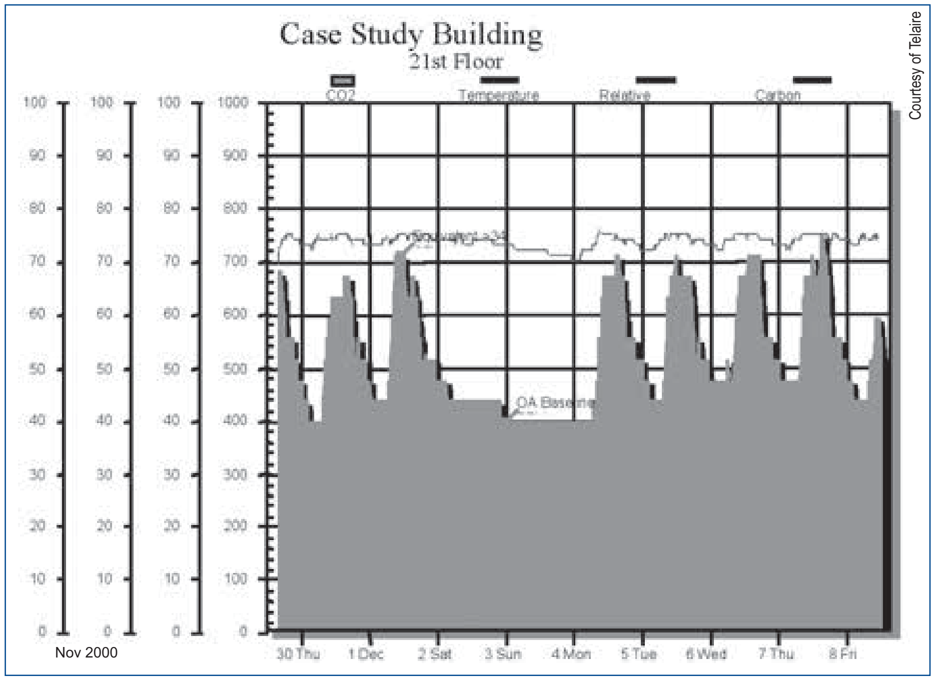


Figure 7. CO_2 trend-logged results from 7 days of monitoring of one location in the building.

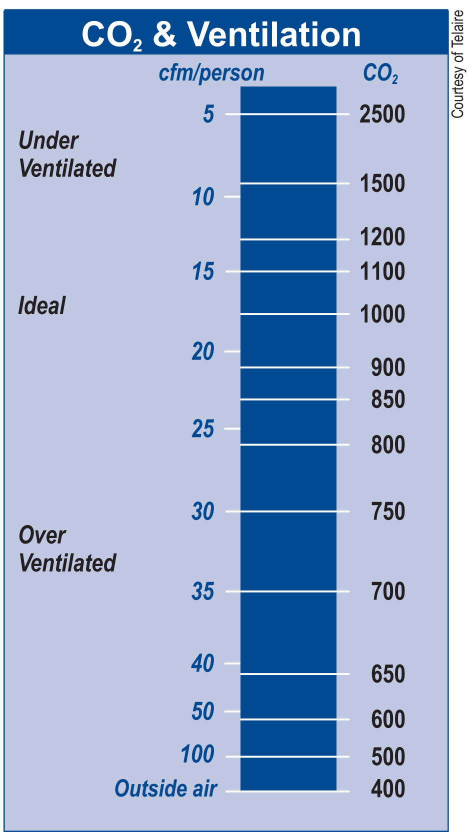


Figure 6. CO_2 to ventilation rate conversion, assuming 400 ppm outside and office-type activity (1.2 MET).

3. Savings potential/pre-project energy analysis

A number of CO_2 sensor manufacturers offer software to analyze the cost savings that will result from applying a CO_2 ventilation control based on occupancy versus a strategy of fixed ventilation during all occupied hours. These programs typically use local hourly weather data and energy cost data. They focus on the energy required to heat and cool various quantities of outside air delivered to the building without undertaking a full-blown energy performance analysis of the building. A similar analysis can be performed using more elaborate building analysis programs such as DOE2.

Using one manufacturer's CO_2 software, the case study building was modeled floor-by-floor to assess the potential annual energy savings. Ventilation rates determined from the trend logging were used to calculate the current fixed ventilation rate by multiplying the cfm/person of ventilation air by the typical peak occupancy on the floor observed during the trend-logged period. For CO_2 control, the modeling program assumed a control algorithm that would proportionately modulate air delivery based on the CO_2 concentration, a typical ventilation control strategy used with CO_2 sensing. It also allowed for simulated occupancy patterns to be varied every 30 minutes to reflect typical occupancy variations through the day. The program correlates the hourly ventilation load with hourly normalized outdoor temperature and dewpoint climactic data to provide an accurate assessment of the HVAC load during all hours while accounting for days when economizer operation results in zero savings as a result of the '"free cooling" effect.

For the case study building, the CO_2 modeling program projected that annual savings of excess of $81,293 would be achievable based on normalized climatic data. Based on energy costs in 2000, these savings are equivalent to a 10% reduction in total energy costs, an average of $3000 in savings per floor annually, and $0.22 per square foot of gross area per year.

4. Implementation assessment

Most floors in the building had open floor plans, with perimeter offices in some cases. In most cases, office doors remained open during occupied hours, allowing free flow of ventilation air between the open central area and the offices. For these floors, it was decided to place one CO_2 sensor on the wall in each quadrant of the building. The rationale for such spacing was that each sensor would cover an area of no greater than 3600 ft^2 of open floor, and two sensors would provide input to each AHU. To ensure that all spaces were adequately ventilated, the ventilation is controlled based on the highest (or worst-case) level of the paired CO_2 sensors. It is important to note that duct sensors were not used because they tend to reflect an average ventilation rate rather than what is actually occurring in the space.

One of the floors had a large number of enclosed meeting/training/video-conferencing rooms that were not often all occupied at the same time. One CO_2 sensor was installed in each of those rooms. In many instances, inter-zonal transfer of air from spaces with lower CO_2 levels will moderate the amount of outside air that must be delivered to the floor, particularly if all rooms are not occupied.

The AHU on each floor required that the relay-operated outside air damper actuator be replaced with a fully modulating electrical motorized actuator to allow modulation of air delivery to each floor. To alleviate the constant negative pressure relationship in the building, the original building static pressure sensor located at the highest point within the building (in the elevator shaft, for unknown reasons) was disconnected. A new building static pressure sensor was located off the lobby level, on the lee side of the building and of the prevailing winds to minimize false positive or negative readings. For the twin exhaust fans, VFDs were added to balance the outside air intake with the required exhaust while maintaining a positive-pressure relationship with the outside. The new outside air CO_2 sensor was installed on the roof, away from any building exhaust and the effects of street-level fluctuations in CO_2.

Critical tasks a building control system or a supporting control and logic system must be able to perform for CO_2 control include these:

- Take input from a number of CO_2 sensors on a floor and determine the highest level.
- Modulate a signal to an actuator or variable-speed fan serving each floor to proportionally modulate the delivery of air based on the CO_2 concentration measured on the floor.
- Control the central building air intake so demand to the entire building can be modulated based on the demand of each floor. (Often a pressure sensor in the main supply air trunk can ensure adequate air delivery.)

Summary of projected energy savings from CO_2 control

Energy	Electricity		Steam		Total
	kWh	Cost[a] ($)	Therms	Cost[b]	
Base	13,966,500	670,800	147,756	122,591	793,391
With CO_2	12,513,896	601,075	134,758	111,023	712,098
Savings	1,452,604	69,725	12,998	11,568	81,293
Savings (%)	10.4		8.8		10.2

[a] Electricity cost = $0.48 per kWh.

[b] Steam cost = $0.89 per therm (natural gas source @81% efficiency).

In summary, the work required to upgrade the building included

- Installing a minimum of four CO_2 sensors and two VFD drives on each of the air intakes for each floor and interfacing these devices to the building control system.
- Programming the building control system to take the CO_2 transmitter signal and regulate air delivery on each floor based on in-space CO_2 levels.
- Moving and replacing the building static pressure sensor.
- Installing variable-speed drives on the building exhaust fans.

It is important to note that for CO_2 control to work in a building, all other HVAC-related systems must be in good operating order. CO_2-related investigations may identify problems not previously recognized and add cost to an upgrade project. In this building, the assessment identified problems with the location of the building pressurization sensor, which had to be relocated and replaced. Logging of CO_2 concentrations in the spaces also indicated that the time-of-day operating schedules on some floors did not match actual occupancy patterns, and a change was recommended. In some cases, a regular check of logged CO_2 data from permanently installed sensors can help keep time-of-day schedules relevant to current occupancy patterns. In some cases, CO_2 data have been used to detect end-of-day occupancy and initiate setback operation when inside levels approach outside concentrations.

5. Payback analysis

The total cost of the building upgrade, including equipment and labor, was estimated at $178,800, which also included $15,000 for the for the pre-project trend analysis. Based on the projected cost savings of $81,293 the CO_2 upgrade project was projected to yield a 2.2-year payback. Based on this methodology and analysis, the project was initiated by the building owner in the late spring of 2001 and completed in July of that year.

Summary of BLCC 5.1-03 life-cycle cost analysis

Study Period 15 years **Discount Rate 3%**	**Base: Current Operational/No CO_2 Control**	**Retrofit of Self Calibrating CO_2 Control**	**Saving from CO_2**
Initial Investment: Cash Requirements	$	$178,800.00	$ (178,800.00)
Future Cost			
Annual & non-annual recurring cost	$	$	$
Energy related cost	$9,414,476	$8,460,875	$953,602
Total	$9,414,476	$8,460,875	$953,602
Net Savings			
PV of non-investment savings			$953,602
Increased total investment			$178,800
Savings-To-Investment Ratio			5.33
Adjusted Internal Rate of Return			15.66%
Simple Payback			3 years
Discounted Payback			3 years

Life-Cycle Cost Analysis

A life-cycle cost analysis of this project using BLCC 5.1-03 was performed using energy and cost data for the building collected for the year 2000 but based on an April 2003 start date, as required by the BLCC program. This procedure probably results in an analysis based on slightly lower costs in the analysis than prevail currently. The study period of 15 years was selected because this is the typical life of most electronic control devices. If a longer period is desired, the user should account for replacement of the sensors at the end of year 15 (approximate cost is $250 to $350 per replacement sensor, including labor). In performing the CO_2 portion of the study, no annual or periodic costs were assumed. In this case, we assumed use of self-calibrating sensor that require no maintenance or calibration over their operating life. Some sensors do require periodic calibration at 3 to 5 years, and users are urged to consider this fact in the selection and cost analysis of their particular installation. The cost of calibration will vary depending on the manufacturer and procedures required. About a third of the sensors sold today have a self-calibrating feature that eliminates maintenance requirements.

The total cost of the building upgrade, including equipment and labor, was estimated at $178,800 (including $15,000 for pre-project trend analysis). The projected annual cost savings was $81,293. The upgrade project was projected to yield a 2.2-year payback.

Post-Implementation Experience

After 6 months of operation, energy data from the building were collected to determine how the CO_2 retrofit and other improvements to the building were performing. Unfortunately, because of changes resulting from a company reorganization, a full 12 months of performance data was not available for analysis. Figure 6 provides a summary of the energy usage for each half-year period during 2000 and 2001. The CO_2 ventilation control system was operated from July to December of 2001. As can be seen from the data, the reductions in energy consumption were in excess of the savings predicted. The difference is probably due to a number of factors, including these:

- Replacement and relocation of the building pressurization sensor probably impacted energy savings, but savings were not predicted for this improvement.
- Time-of-day schedules were reprogrammed based on actual occupancy, and building exhaust fans were adjusted to minimum levels during unoccupied hours. The change that probably contributed additional energy savings to savings predicted.
- The year 2001 was milder than 2000 and had 20% fewer cooling degree days and 4% fewer heating degree days.

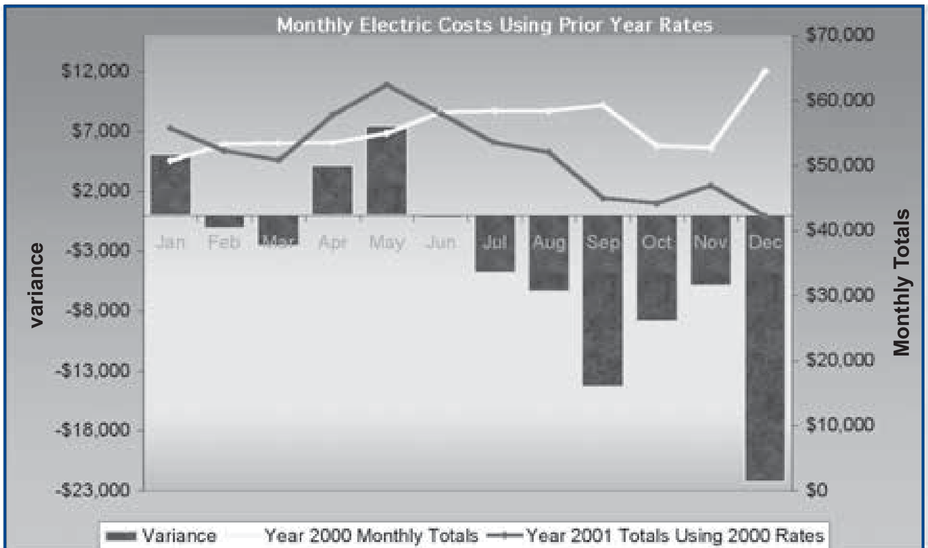
According to the facility manager, the tenants were satisfied with the comfort levels in the space following the retrofit and no longer complained of high humidity levels in the building during summer months. Because the logged CO_2 data showed the space to be significantly over-ventilated, reducing ventilation with CO_2 control reduced the amount of humid outside air drawn into the building and allowed the cooling system to maintain better control of humidity.

The following charts show energy performance, electricity costs, and steam costs before and after the CO_2-based DCV retrofit.

Before-and-after energy performance

Energy Cost	2000 Jan–June	2000 July–Dec	2001 Jan–June	2001 July–Dec*
Electricity kwh	6,357,000	7,609,500	6,606,000	6,219,000
Electricity ($)	$305,136	$365,256	$317,088	$298,512
Steam (therm)	71,918	75,838	84,523	22,960
Steam ($)	$64,007	$67,496	$75,225	$20,434
Total ($)	$369,143	$432,752	$392,313	$318,946
Annual ($)		$801,895		$711,260
6 month savings comparing July–Dec 2000 vs 2001				
Electric ($)				$66,744
Steam ($)				$47,061
Total ($)				$113,805

*CO_2 Control in Operation

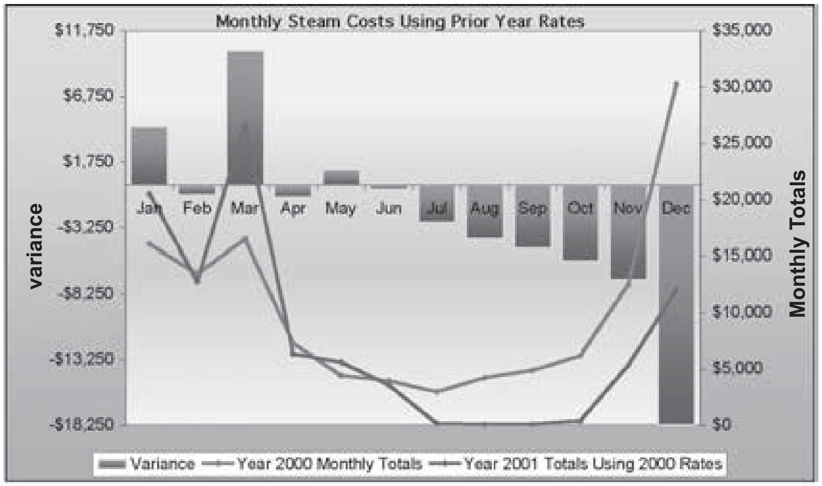


Courtesy of Telaire

	Monthly Kwh Usage 2000	Year 2000 Cost Per Kwh	Year 2000 Monthly	Monthly Kwh Usage 2001	Year 2001 Totals Using 2000 Rates	Variance
Jan	931,500	$0.0545	$50,751	1,024,500	$55,817.49	$5,067
Feb	1,032,000	$0.0517	$53,344	1,011,000	$52,258.07	-$1,085
Mar	1,035,000	$0.0516	$53,421	985,500	$50,866.04	-$2,555
Apr	1,042,500	$0.0514	$53,607	1,123,500	$57,772.45	$4,165
May	1,095,000	$0.0502	$54,962	1,245,000	$62,490.63	$7,529
Jun	1,221,000	$0.0477	$58,212	1,216,500	$57,997.49	-$215
Jul	1,227,000	$0.0476	$58,382	1,126,500	$53,599.93	-$4,782
Aug	1,297,500	$0.0450	$58,381	1,156,500	$52,036.64	-$6,344
Sep	1,317,000	$0.0450	$59,319	999,000	$44,995.94	-$14,323
Oct	1,123,500	$0.0472	$53,042	936,000	$44,189.89	-$8,852
Nov	1,153,500	$0.0458	$52,777	1,024,500	$46,874.76	-$5,902
Dec	1,491,000	$0.0433	$64,545	976,500	$42,272.43	-$22,273

Figure 8. Shown are the monthly costs (right scale) for the 'baseline' months 2000 (light line) and for the months of 2001 (dark line) calculated using 2000 rates. The variance (left scale) is shown by the columns. A major vector change occurred beginning in July (as the first phases of DCV were coming on-line) that is known not to be weather related (the minor variance in Feb/Mar is known to reflect a shift in the weather load).

Before and After Steam Usage for Case Study Building



Courtesy of Telaire

	Monthly Steam Usage 2000	Year 2000 Cost Per M^3 Lbs	Year 2000 Monthly	Monthly Steam Usage 2001	Year 2001 Totals Using 2000 Rates	Variance
Jan	1,647	$9.7365	$16,036	2,103	$20,475.88	$4,440
Feb	1,259	$10.7220	$13,499	1,189	$12,748.43	-$751
Mar	860	$19.1683	$16,485	1,395	$26,739.80	$10,255
Apr	672	$10.8123	$7,266	585	$6,325.20	-$941
May	366	$12.0920	$4,426	462	$5,586.49	$1,161
Jun	333	$11.7691	$3,919	304	$3,577.80	-$341
Jul	270	$10.9787	$2,964	11	$120.77	-$2,843
Aug	333	$12.6317	$4,206	6	$75.79	-$4,131
Sep	381	$12.7423	$4,855	5	$63.71	-$4,791
Oct	523	$11.7887	$6,166	33	$389.03	-$5,776
Nov	1,166	$10.7147	$12,493	495	$5,303.78	-$7,190
Dec	2,744	$11.0335	$30,276	1,090	$12,026.47	-$18,249

Figure 9. Shown are the monthly costs (right scale) for the 'baseline' months in 2000 (lighter line) and the cost for the months of 2001 (darker line) calculated using 2000 rates. The variance (left scale) is shown by the columns. Since July, savings have occurred each month as a direct result of the CO_2 retrofit project, whereas the variance in March 2001 is known to be due to a shift in weather load.

The Technology in Perspective

The Technology's Development

CO_2-based DCV is an emerging technology with currently limited but increasing market penetration. The literature on CO_2-based DCV consistently predicts that the technology will become a common ventilation strategy.

CO_2 sensors for DCV regulation are a relatively mature product, having been on the market since about 1990. The first CO_2 sensors were expensive, unreliable, and difficult to keep calibrated. However, manufacturers claim to have resolved those problems—units currently available generally are self-calibrating and similar to thermostats in price and reliability. Although manufacturers say most sensors are designed to operate for 5 years without maintenance, regular inspection to verify calibration and proper operation is still recommended.

Interest in DCV was spurred by ASHRAE 62, which increased the requirement for ventilation air in buildings to safeguard IAQ. Building managers became concerned that the increased ventilation level was driving up energy costs by introducing unnecessarily large amounts of fresh air that had to be cooled, heated, dehumidified. CO_2-controlled DCV offers a method of regulating ventilation levels so as to satisfy the requirements of ASHRAE 62 without over-ventilating.

DCV based on CO_2 sensing is recognized as a viable strategy by the HVAC and building industries:

- CO_2 sensors are sold by all major HVAC equipment and controls companies.
- More than a dozen manufacturers produce CO_2 sensors for DCV.
- Most manufacturers of thermostats and economizers now integrate CO_2 sensors into their products, and major manufacturers of packaged rooftop HVAC systems offer factory-installed CO_2 sensors as an option.
- ASHRAE 90 requires CO_2 sensors for DCV in high-density applications.
- In the next revision of its building code, California will begin requiring CO_2-based DCV in all buildings housing 25 people or more per 1000 ft^2.
- A proposed change in the Oregon building code would require DCV for HVAC systems with ventilation air requirements of at least 1500 cfm, serving areas with an occupant factor of 20 or less.
- ASHRAE Standard 62, the IMC (which establishes minimum regulations for mechanical systems), and some state and local building codes recognize CO_2-based DCV.
- The U.S. Green Building Code gives points in its LEED rating system for use of CO_2-based DCV.

Technology Outlook

CO_2-based DCV appears likely to become a commonplace ventilation strategy for large commercial and institutional buildings as building operators seek ways to balance building code ventilation requirements and IAQ concerns with the need to control energy demand and operating costs. Equipment development is encouraging the adoption of the technology. Prices of CO_2 sensors for DCV prices have dropped by about 50% since 1990, and as market penetration increases, are expected to fall further. Most HVAC equipment makers are including factory installation of CO_2 sensors for DCV as an option in their large packaged systems. At least one major manufacturer has adapted its equipment line to accommodate CO_2-based DCV in every piece of ventilation equipment it makes. This implicit endorsement of the technology by equipment makers makes its adoption simpler and less expensive, at least in new installations, and will almost certainly contribute to developing a broader market for CO_2-based DCV.

The emergence of wireless, self-powered multi-parameter (CO_2/temperature/humidity) sensors designed for permanent installation is expected to further increase the speed of adoption of DCV. They have the potential to lower the total cost of deployment, making installation simpler and faster and improving paybacks.

As installers, HVAC engineers, and maintenance personnel accumulate more hands-on experience with the controls and operational issues CO_2-based DCV presents, and gain more expertise in troubleshooting and resolving problems, the comfort level with the technology should increase. The increased familiarity is likely to increase its acceptance.

Manufacturers

The following list includes companies identified as manufacturers of CO_2 sensors for demand-controlled ventilation at the time of this report's publication. The list does not include manufacturers of CO_2 sensors designed for use in safety equipment or for control of conditions in laboratories or industrial processes that are not appropriate for demand-controlled ventilation. We made every effort to identify all manufacturers of the equipment, including an extensive search of the *Thomas Register*; however, this listing is not purported to be complete or to reflect future market conditions.

AirTest Technologies
1520 Cliveden Avenue
Delta, BC V3M 6J8
Tel: 888-855-8880, 604-517-3888
Fax: 604-517-3900
www.airtesttechnologies.com
mike.schell@airtesttechnologies.com

Carrier Corporation
6304-T Thompson Rd., P.O. Box 4808
Syracuse, NY 13221 4808
Tel: 315-432-6000
www.carrier.com/

DetectAire, Inc.
5973 Encina Road, Suite 109
Goleta, California 93107
Tel: 805-683 1117
www.detectaire.com
(DetectAire markets wireless sensors)

Digital Control Systems, Inc.
7401-T S.W. Capitol Hwy.
Portland, OR 97219 2431
Tel: 503-246-8110 Fax: 503-246-6747
http://www.dcs-inc.net

Honeywell Control Products
11 W. Spring St.
Freeport, IL 61032
Tel: 815-235-6847 Fax: 815-235-6545
Cable: Honeywell-Freeport
http://www.honeywell.com/sensing

Johnson Controls, Inc.
Controls Group
507 E. Michigan St., P.O. Box 423
Milwaukee, WI 53201 0423
Tel: 800-972-8040 Fax: 414-347-0221

Kele
3300 Brother Blvd.
Memphis, TN 38133
Tel: 888-397-5353 Fax: 901-382-2531
Email: info@kele.com
www.kele.com

MSA
MSA Bldg., P.O. Box 426
Pittsburgh, PA 15230 0426
Tel: 412-967-3000
Fax: 412-967-3450 or 800-967-0398
Cable: MINSAF
http://www.msanet.com

Telaire Systems, Inc.
6489 Calle Real, Dept. TR
Goleta, CA 93117
Tel: 805-964-1699 Fax: 805-964-2129

Texas Instruments, Inc.
Commercial Sensors & Controls Div.
34 Forest St., MS 20-22, P.O. Box 2964
Attleboro, MA 02703-0964
Tel: 800-788-8661, Ext. 400
http://www.tisensors.com

Thermo Gas Tech
8407 Central Ave.
Newark, CA 94560
Tel: 888-243-6167 Fax: 510-794-6201
Or call: 510-745-8700
http://www.thermogastech.com

Vaisala, Inc.
100 Commerce Way
Woburn, MA 01801 1008
Tel: 800-408-5266 Fax: 781-933-8029
http://www.vaisala.com

Veris Industries, Inc.
10831-T S.W. Cascade Ave.
Portland, OR 97223
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Who is Using the Technology

Federal Sites

The Pentagon
Robert Billak
Department of Defense
Pentagon Heating and Refrigeration Plant
300 Boundary Channel Dr.
Arlington, VA 22020

Navy Annex
Robert Billak
Department of Defense
Pentagon Heating and Refrigeration Plant
300 Boundary Channel Dr.
Arlington, VA 22020

Beaufort Marine Corps Air Station
Neil Tisdale, Utilities Director
Beaufort, South Carolina

Non-Federal Sites

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Facilities Service Department
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West Lafayette, IN 47907
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Oberlin University
Adam Joseph Lewis Center
for Environmental Studies
Leo Evans
122 Elm Street
Oberlin, Ohio 44074

Reedy Creek Energy Services (The Walt Disney Company)
Paul Allen
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paul.allen@disney.com

Shorenstein Reality Services
Bob Landram
816-421-4997
blandram@shorenstein.com

For Further Information

Associations

American Society of Heating, Refrigerating and Air-Conditioning Engineers
American Society for Testing and Materials
U.S. Green Building Council
American Indoor Air Quality Council

Design and Installation Guides

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Case Studies

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Codes and Standards

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Appendix A

Federal Life-Cycle Costing Procedures and the BLCC Software

Federal agencies are required to evaluate energy-related investments on the basis of minimum life-cycle costs (10 CFR Part 436). A life-cycle cost evaluation computes the total long-run costs of a number of potential actions, and selects the action that minimizes the long-run costs. When considering retrofits, sticking with the existing equipment is one potential action, often called the *baseline* condition. The life-cycle cost (LCC) of a potential investment is the present value of all of the costs associated with the investment over time.

The first step in calculating the LCC is the identification of the costs. *Installed Cost* includes cost of materials purchased and the labor required to install them (for example, the price of an energy-efficient lighting fixture, plus cost of labor to install it). *Energy Cost* includes annual expenditures on energy to operate equipment. (For example, a lighting fixture that draws 100 watts and operates 2,000 hours annually requires 200,000 watt-hours (200 kWh) annually. At an electricity price of $0.10 per kWh, this fixture has an annual energy cost of $20.) *Nonfuel Operations and Maintenance* includes annual expenditures on parts and activities required to operate equipment (for example, replacing burned out light bulbs). *Replacement Costs* include expenditures to replace equipment upon failure (for example, replacing an oil furnace when it is no longer usable).

Because LCC includes the cost of money, periodic and aperiodic maintenance (O&M) and equipment replacement costs, energy escalation rates, and salvage value, it is usually expressed as a present value, which is evaluated by

$$LCC = PV(IC) + PV(EC) + PV(OM) + PV(REP)$$

where PV(x) denotes "present value of cost stream x,"
IC is the installed cost,
EC is the annual energy cost,
OM is the annual nonenergy O&M cost, and
REP is the future replacement cost.

Net present value (NPV) is the difference between the LCCs of two investment alternatives, e.g., the LCC of an energy-saving or energy-cost-reducing alternative and the LCC of the existing, or baseline, equipment. If the alternative's LCC is less than the baseline's LCC, the alternative is said to have a positive NPV, i.e., it is cost-effective. NPV is thus given by

$$NPV = PV(EC_0) – PV(EC_1)) + PV(OM_0) – PV(OM_1)) + PV(REP_0) – PV(REP_1)) – PV(IC)$$

or

$$NPV = PV(ECS) + PV(OMS) + PV(REPS) – PV(IC)$$

where subscript 0 denotes the existing or baseline condition,
subscript 1 denotes the energy cost saving measure,
IC is the installation cost of the alternative (note that the IC of the baseline is assumed zero),
ECS is the annual energy cost savings,
OMS is the annual nonenergy O&M savings, and
REPS is the future replacement savings.

Levelized energy cost (LEC) is the break-even energy price (blended) at which a conservation, efficiency, renewable, or fuel-switching measure becomes cost-effective (NPV >= 0). Thus, a project's LEC is given by

$$PV(LEC*EUS) = PV(OMS) + PV(REPS) – PV(IC)$$

where EUS is the annual energy use savings (energy units/yr). Savings-to-investment ratio (SIR) is the total (PV) savings of a measure divided by its installation cost:

$$SIR = (PV(ECS) + PV(OMS) + PV(REPS))/PV(IC).$$

Some of the tedious effort of life-cycle cost calculations can be avoided by using the Building Life-Cycle Cost software, BLCC, developed by NIST. For copies of BLCC, call the EERE Information Center (877) 337-3463.

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About FEMP's New Technology Demonstrations

The Energy Policy Act of 1992 and subsequent Executive Orders mandate that energy consumption in federal buildings be reduced by 35% from 1985 levels by the year 2010. To achieve this goal, the U.S. Department of Energy's Federal Energy Management Program (FEMP) sponsors a series of activities to reduce energy consumption at federal installations nationwide. FEMP uses new technology demonstrations to accelerate the introduction of energy-efficient and renewable technologies into the federal sector and to improve the rate of technology transfer.

As part of this effort, FEMP sponsors the following series of publications that are designed to disseminate information on new and emerging technologies:

Technology Focuses—brief information on new, energy-efficient, environmentally friendly technologies of potential interest to the federal sector.

Federal Technology Alerts—longer summary reports that provide details on energy-efficient, water-conserving, and renewable-energy technologies that have been selected for further study for possible implementation in the federal sector.

Technology Installation Reviews—concise reports describing a new technology and providing case study results, typically from another demonstration program or pilot project.

Other Publications—we also issue other publications on energy-saving technologies with potential use in the federal sector.

More on Federal Technology Alerts

Federal Technology Alerts, our signature reports, provide summary information on candidate energy-saving technologies developed and manufactured in the United States. The technologies featured in the FTAs have already entered the market and have some experience but are not in general use in the federal sector.

The goal of the FTAs is to improve the rate of technology transfer of new energy-saving technologies within the federal sector and to provide the right people in the field with accurate, up-todate information on the new technologies so that they can make educated judgments on whether the technologies are suitable for their federal sites.

The information in the FTAs typically includes a description of the candidate technology; the results of its screening tests; a description of its performance, applications, and field experience to date; a list of manufacturers; and important contact information. Attached appendixes provide supplemental information and example worksheets on the technology.

FEMP sponsors publication of the FTAs to facilitate information-sharing between manufacturers and government staff. While the technology featured promises significant federal-sector savings, the FTAs do not constitute FEMP's endorsement of a particular product, as FEMP has not independently verified performance data provided by manufacturers. Nor do the FTAs attempt to chart market activity vis-a-vis the technology featured. Readers should note the publication date on the back cover, and consider the FTAs as an accurate picture of the technology and its performance at the time of publication. Product innovations and the entrance of new manufacturers or suppliers should be anticipated since the date of publication. FEMP encourages interested federal energy and facility managers to contact the manufacturers and other federal sites directly, and to use the worksheets in the FTAs to aid in their purchasing decisions.

Federal Energy Management Program

The federal government is the largest energy consumer in the nation. Annually, the total primary energy consumed by the federal government is 1.4 quadrillion British thermal units (quads), costing $9.6 billion. This represents 1.4% of the primary energy consumption in the United States. The Federal Energy Management Program was established in 1974 to provide direction, guidance, and assistance to federal agencies in planning and implementing energy management programs that will improve the energy efficiency and fuel flexibility of the federal infrastructure.

Over the years, several federal laws and Executive Orders have shaped FEMP's mission. These include the Energy Policy and Conservation Act of 1975; the National Energy Conservation and Policy Act of 1978; the Federal Energy Management Improvement Act of 1988; the National Energy Policy Act of 1992; Executive Order 13123, signed in 1999; and most recently, Executive Order 13221, signed in 2001, and the Presidential Directive of May 3, 2001.

FEMP is currently involved in a wide range of energy-assessment activities, including conducting new technology demonstrations, to hasten the penetration of energy-efficient technologies into the federal marketplace.

A Strong Energy Portfolio for a Strong America

Energy efficiency and clean, renewable energy will mean a stronger economy, a cleaner environment, and greater energy independence for America. Working with a wide array of state, community, industry, and university partners, the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy invests in a diverse portfolio of energy technologies.

Log on to FEMP's Web site for information about New Technology Demonstrations

www.eere.energy.gov/femp/

You will find links to

- A New Technology Demonstration Overview
- Information on technology demonstrations
- Downloadable versions of publications in Adobe Portable Document Format (pdf)
- A list of new technology projects under way
- Electronic access to a regular mailing list for new products when they become available
- How Federal agencies may submit requests to us to assess new and emerging technologies

For More Information

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www.eere.energy.gov/femp

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Indoor Environment Quality (User Comfort, Health and Behaviour)

The Effect of Indoor Temperature and CO_2 Levels on Cognitive Performance of Adult Females in a University Building in Saudi Arabia

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Abstract

Temperatures and indoor CO2 levels within buildings play a crucial role, not only for energy consumption, but also for occupant performance and particularly cognitive performance regarding all mental activities such as thinking, reasoning, and remembering. Using a multi-variable multilevel approach, the effects of classroom temperature and CO2 levels were estimated on vigilance and memory tasks. The analysis is based on two classrooms' physical environmental measurements data in a university located in Saudi Arabia. Participant votes on standard subjective thermal rating scales were collected from 499 adult female students, which were correlated with relevant environmental parameters such as humidity, radiant temperature, air velocity and self-reported clothing levels. Performance against two neurobehavioral cognitive tests was evaluated. The effects of three temperature levels were investigated. Statistically significant associations were observed between the cognitive test outomes and the investigated exposure conditions of classrooms' temperature and CO2 concentration levels. The associations remained significant after adjusting for confounding variables.

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Keywords: Indoor temperature; CO_2 concentration levels; Cognitive performance; Education and tasks conducive to learning.

1. Introduction

Students' ability to sustain attention and concentration are key requirements for achieving high performance. According to a number of studies, classrooms' environmental factors such as temperature and ventilation rates are

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known to disrupt concentration and attention in educational buildings, and are likely to undermine academic performance [1]. In educational buildings, classroom ventilation has been already recognized as an important determinant of indoor air quality since the beginning of the 20th century; however, studies worldwide up to date showed that classrooms ventilation requirements in educational buildings are not met yet in most buildings. With specific regards to Saudi Arabia, recent evidence was provided based on data collected from 36 schools indicating that classroom ventilation rates in Saudi Arabia do not meet building standards [2]. Consequently, this has led to higher indoor Carbon dioxide (CO_2) concentrations in buildings. High CO_2 levels suggest that there is poor ventilation and movement of air in a space, which could lead to increased concentrations of a variety of irritants.

Moreover, providing sufficient classrooms' ventilation rates alone is not sufficient to provide a good learning environment. Room temperature has been found to influence productivity directly and also indirectly through its impact on prevalence of SBS symptoms or satisfaction with air quality [3]. In addition, according to a number of studies, thermal environment that causes thermal discomfort may affect performance. However, scarce data and very little empirical evidence is currently available from the mechanically ventilated and cooled educational buildings located in the hot climates regions and particularly from the Arabian Gulf Peninsula where energy has become cheap and affordable. It is of a particular importance to investigate the effects in air-conditioned buildings since most air conditioners re-circulate a significant portion of the indoor air to maintain comfort and reduce energy costs associated with heating or cooling outside air. Inhaling the circulated air can cause adverse health problems and respiratory diseases attributed to the airborne pollutants [4]. The central nervous system has also been proposed to be a target organ for the detrimental effects of airborne pollutants [5]. In addition, females' educational buildings are presumed to be relatively in a poorer condition and left behind in Saudi Arabia relative to males' educational buildings because of cultural issues, and less attention is paid to them [6]. Furthermore, the effects of room temperatures and indoor air quality are mostly provided from studies conducted in educational buildings which are mostly based on schoolwork by children. On-going research is focusing on children performances as they are more vulnerable to effects from environmental hazards. Nonetheless, the science of developmental neuropsychology recognized that more complex thinking executive functions (such as perception of time, abstract understanding of language and selective attention) occur approximately from the age of 9 to 23 years [7].

Therefore, the main objective of this study is to further underpin the science of IAQ and cognitive performance whilst helping to understand the implications for educational buildings' design on the ability of students to learn in the mechanically ventilated and cooled buildings located in hot climates whilst considering the air-conditioners' acclimation effect in this context of study. Continuous performance test (CPT) was selected as a representative of an attention task and match to sample (MTS) was selected as a representative of a working memory task. Attention and working memory are two key requirements for the tasks conducive to learning. In this study, a multi-variable multilevel statistical modelling approach was adopted which took into account of the nested structure of the data whilst adjusting for the confounding variables including thermal comfort sensations, age, physical activity, clothing levels, stress, caffeine intake, sleeping hours, noise levels, air-conditioners' set temperature at home, as well as ethnic background. Only one recent study has adopted multi-variable multilevel statistical modelling approach; nevertheless, none of these confounding variables were included in their model and the sample size was much smaller whereby no statistically significant associations have been obtained.

2. Research Methods

2.1. Protocol of the study

A female university building located in Jeddah, Saudi Arabia, was selected for the study. Four hundred and ninety nine female subjects were tested under nine different exposure conditions combining temperatures (20°C, 23°C and 25°C) and CO_2 levels (600 ppm, 1000 ppm and 1800 ppm). Participants performed eight different cognitive tests (only two of which are discussed in this paper, namely: continuous performance test (CPT) and match to sample (MTS)). In parallel, the participants evaluated their thermal comfort sensations during the exposures. Within-subjects design was adopted where the same participants were exposed to the same exposure conditions, where exposures took place on the same weekday to avoid any influence of weekday on the within-subject difference between conditions. BARS battery "behavioral assessment and research system" [8] was used for the cognitive performance assessment.

Only temperature and CO_2 concentration levels were the independent variables which were manipulated whilst the other parameters were kept within constant ranges during the exposure conditions (namely: sound levels, lighting intensity, air velocity, and relative humidity). The experiment took place every day from Saturday to Wednesday and was always on the same time of the day where each exposure condition lasted for 5 weeks. Two identical classrooms were selected and were used based on their availability. In addition, both classrooms were located in a central location inside the building, which were not exposed to external heat radiation and thus the effect or radiant temperature was eliminated as well as the effect of sun light. Monitoring of environmental conditions, collection of subjective measurements and evaluating the cognitive performance for the tasks selected for the study all took place simultaneously. Cognitive performance assessment started after around 20 minutes from the time the participants entered the classroom in order to allow them enough time to become acclimatised to the classroom's adjusted exposure conditions.

On a day prior to the first exposure the participants attended a practice session. Participants were instructed to forgo their morning coffee on the days of the experimental exposures, and not to drink sodas, energy drinks, as well as avoiding eating chocolate. Participants were also instructed to avoid intense physical activity for at least 12 hours prior to participation and to have adequate amount of sleep during the nights before participation for not less than 7 hours. No restrictions were made on clothing; participants were allowed to wear their typical cloths during the experimental exposures. The participants were instructed to use the computers that were equipped with the cognitive performance software, as these computers were chosen not to be located directly under the ceiling air-conditioners' diffusers. The duration of the assessment of the cognitive tasks lasted for around 35 min. The subjective questionnaire responses of the participants were collected during the exposures directly after the participants finished performing the cognitive tasks. In order to overcome the carry-over effect, known as the main disadvantage of the within-subject design, the parameters of the cognitive tasks were modified in terms of the sequence of the appearance of stimuli, their shapes, their corresponding response keys, the sequence of digits, and the patterns in the match to sample task, number of trials, duration of tasks, stimulus durations, and the interval between presentation of sample stimulus and distractors.

2.2. Experimental conditions

With regards to indoor temperature, based on a pilot study conducted prior to the intervention seeking information about the base line condition in the case study building, the maximum operative temperature the participants were able to tolerate was 25°C. Furthermore, according to a facility management survey which was conducted prior to the intervention as well seeking information about the most common temperature set in educational buildings in Jeddah-Saudi Arabia, 20ºC was found to the most common temperature set in more than 80% of the surveyed buildings. Therefore, the indoor temperatures set during the conditions of exposures were 20°C, 23°C and 25°C. With regards to CO_2 levels, the air conditioning system used in the case study building is a central system (CAV). The damper of the fresh air damper was shut down through the building management system (BMS). The command of the dampers was put in a manual mode which made the dampers no longer controlled by the BMS and hence they did not open by the BMS when the CO_2 exceeded the adjusted CO_2 set point to let fresh air enter the classrooms. CO_2 levels ~1800 ppm were the maximum achieved and ~600 ppm were the minimum achieved. Therefore, the CO_2 levels set during the exposure conditions were 600, 1000, and 1800 ppm.

2.3. Measurements

The measurements were collected continuously from 8:30 AM until 3:00 PM. Air temperature, relative humidity, lighting intensity and noise levels were measured by HOBO data loggers. Air velocity was monitored using Testo Large Vane Anemometer Kit and CO_2 concentrations using Telaire 7001 infra-red gas monitor. The equipment were placed in a central location in the classrooms since the outlets and inlets of the air conditioners are distributed equally in the ceiling. Equipment were placed at the head height of a seated person.

2.4. Statistical analysis

The statistical analysis was based on a multi-variable multilevel approach. First, uni-variable multi-level mixed effect models were performed to check for any association between the confounders of this study with the accuracy and speed of performance. Age, ethnicity, physical activity, air-conditioners' set temperatures at home, caffeine intake, sleeping hours, thermal comfort sensations, clothing levels, ambient noise, stress, and any reported symptoms by the participants were the confounders found significantly associated. Accordingly, a multi-variable model was performed which adjusted for the associated confounders. The analysis was performed using STATA software.

3. Results

All measured physical parameters describing the conditions in the monitored classrooms during different exposures are listed in Table 1. According to the subjective responses, 99% of participants slept for more than 7 hours during the nights prior to exposures, nobody had caffeinated drinks within 2 hrs prior to participation, and all participants had breakfast on the same day of participation. No great variation in clothing levels was observed; over 90% wore cloths worth 0.85 clo, only 2% reported dissatisfaction with the ambient noise leading to inability to focus, and nobody reported being stressed due to personal reasons.

Table 1. Measured parameters during the exposure conditions (mean ± SD).

Condition	Air temperature (°C)	CO_2 concentration (ppm)	Relative humidity (%)	Air Velocity (m/s)	Light Intensity (Lux)	Noise Levels (dB(A))
Condition 1	20.0 ± 0.2	600 ± 30	42 ± 3	0.15 ± 0.02	400 ± 50	34 ± 2
Condition 2	20.0 ± 0.2	1000 ± 40	42 ± 3	0.11 ± 0.02	400 ± 50	34 ± 2
Condition 3	20.0 ± 0.2	1800 ± 60	42 ± 3	0.08 ± 0.02	400 ± 50	34 ± 2
Condition 4	23.0 ± 0.2	600 ± 30	40 ± 3	0.13 ± 0.02	400 ± 50	34 ± 2
Condition 5	23.0 ± 0.2	1000 ± 40	40 ± 3	0.10 ± 0.02	400 ± 50	34 ± 2
Condition 6	23.0 ± 0.2	1800 ± 60	40 ± 3	0.07 ± 0.02	400 ± 50	34 ± 2
Condition 7	25.0 ± 0.2	600 ± 30	38 ± 3	0.13 ± 0.02	400 ± 50	34 ± 2
Condition 8	25.0 ± 0.2	1000 ± 40	38 ± 3	0.09 ± 0.02	400 ± 50	34 ± 2
Condition 9	25.0 ± 0.2	1800 ± 60	38 ± 3	0.05 ± 0.02	400 ± 50	34 ± 2

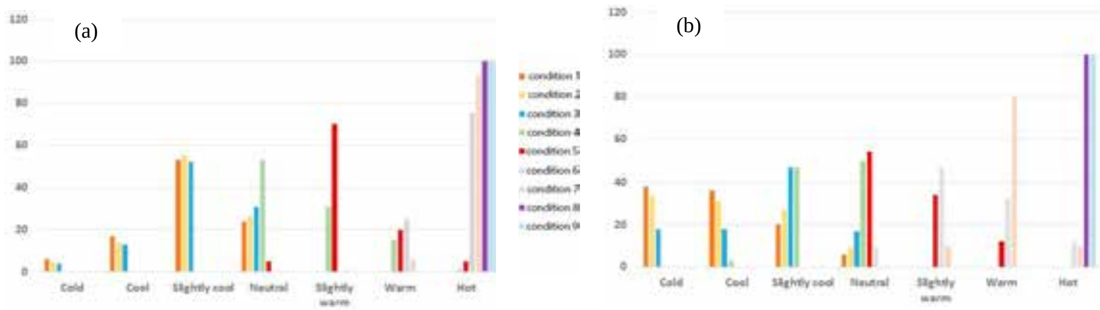

Fig. 1. (a) Thermal sensation votes of the Saudi participants at the different exposure conditions investigated in the study; (b) Thermal sensation votes of the non-Saudi participants at the different exposure conditions investigated in the study.

The results also indicated that there were statistically significant associations between all exposure conditions with ethnicity, thermal comfort sensations, air-conditioner (AC) set temperature at home, and the symptoms of intolerable thermal discomfort that impairs focusing ability and symptoms like headache, fatigue and dizziness with the percentages of errors for both cognitive tasks. The estimated effect sizes are listed in Table 2. For the speed of reaction, significant fast performance was observed at the conditions when temperature was set at 25°C and at 23°C relative to 20°C for both cognitive tasks. Significant slowed performance was observed during the conditions when temperature was set at 20°C relative to 23°C and 25°C. In addition, results indicated that the subjective ratings of the thermal sensation votes of the participants varied by ethnicity. For the Saudi participants, exposure to temperature 23°C reduced their thermal sensations to slightly warm from cool and/or slightly cool at 20°C, while at 25°C almost all participants perceived the ambient thermal environment as uncomfortable hot. However, the non-Saudi participants perceived the thermal environment as slightly cool and/or neutral at 23°C. Fewer participants reported feeling hot at 25°C relative to the Saudi participants while more participants reported feeling cold, cool and slightly cool at 20°C. According to participants' subjective responses, mean AC temperature set at home by the Saudi participants was lower by 2°C relative to that reported by the non-Saudi participants.

Table 2. Cognitive performance scores at the different exposure conditions investigated in the study.

	Uni-variable model CPT accuracy (error%) estimate (95% CI)	Multi-variable model CPT accuracy (error%) estimate (95% CI)	Uni-variable model MTS accuracy (error%) estimate (95% CI)	Multi-variable model MTS accuracy (error%) estimate (95% CI)
Condition 2 vs. Condition 1	2.74 (1.05, 3.43)*	3.44 (2.03, 4.85)*	2.33 (1.82, 2.85)*	5.26 (4.72, 5.79)*
Condition 3 vs. Condition 1	6.42 (5.05, 7.79)*	7.75 (6.38, 8.12)*	5.87 (5.35, 5.38)*	12.16 (10.18, 14.15)*
Condition 4 vs. Condition 1	4.19 (3.77, 4.60)*	6.53 (5.81, 7.25)*	-1.19 (-1.71, -1.50)*	-5.45 (-6.72, -4.58)*
Condition 5 vs. Condition 1	11.61 (10.20, 12.02)*	15.22 (14.86, 16.59)*	9.95 (9.57, 10.33)*	16.74 (15.80, 17.68)*
Condition 6 vs. Condition 1	14.79 (13.41, 15.17)*	20.56 (19.27, 21.86)*	10.80 (10.28, 11.31)*	21.34 (20.88, 22.81)*
Condition 7 vs. Condition 1	5.96 (4.55, 6.37)*	7.76 (6.67, 8.87) *	7.85 (6.34, 8.37)*	12.16 (11.34, 12.98)*
Condition 8 vs. Condition 1	14.75 (13.34, 15.17)*	20.96 (19.61, 21.30)*	14.42 (13.90, 15.93)*	25.03 (24.53, 26.54)*
Condition 9 vs. Condition 1	22.70 (21.28, 23.11)*	35.08 (34.20, 36.77)*	21.71 (20.34, 22.08)*	32.82 (31.31, 33.33)*
Confounding factors controlled: Ethnicity (Saudi vs. other)	-	-1.63 (-2.30, -0.95)*	-	-1.71 (-2.53, -0.88)*
Thermal Sensation Votes:				
-Cold vs. neutral	-	5.67 (4.10, 6.33)*	-	13.06 (12.19, 14.94)*
-Cool vs. neutral	-	-1.71 (-2.25, -0.17)*	-	-1.09 (-1.46, -0.37)*
-Slightly cool vs. neutral	-	-2.09 (-3.15, -1.03)*	-	-2.47 (-3.44, -1.49)*
-Slightly warm vs. neutral	-	5.22 (4.52, 6.90)*	-	-0.60 (-1.06, -0.21)*
-Warm vs. neutral	-	7.52 (6.01, 8.05)*	-	8.82 (7.33, 9.97)*
-Hot vs. neutral	-	10.90 (9.99, 11.81)*	-	16.06 (15.58, 17.55)*
Temperature at home (per unit increase between 18°C-24°C)	-	-0.80 (-0.97, -0.62)*	-	-1.01 (-1.11,-1.90)*
Reported intolerable thermal discomfort that impairs focusing ability	-	5.06 (4.14, 6.26)*	-	8.06 (7.50, 9.66)*
Other symptoms reported which impaired the focusing ability	-	5.25 (4.22, 6.70)*	-	8.35 7.01, 9.71)*

*p <0.001

4. Discussion

First, with regards to the discrepancy of participants' thermal sensation votes according to their ethnicity, according to Brager & de Dear [9], human adaptation to the thermal environment and expectations as well as past thermal exposure experience play a crucial role in the thermal comfort sensation. Yamtraipat et al. [10] indicated that acclimatization to using home air-conditioners could affect thermal comfort sensation considerably. In addition, after adding the variable of ethnicity in the final model, Saudi participants had significant lower percentages of errors by ~2% relative to the non-Saudi participants. Previous studies also observed differences between students of different ethnic backgrounds while learning in terms of temperature preference [e.g.:11]. Furthermore, after adding the variable of AC set temperature at home to the uni-variable original model, the percentages of errors decreased significantly by ~1% for each unit increase in temperature in the range between 18°C-24°C. It could be postulated that the physiological expectation and repeated exposures can cause AC acclimatization effect to home temperature, which can affect the accuracy in performance significantly. Results also revealed that the estimated effects of temperature on accuracy varied according to the nature of task; however, exposures to CO_2 levels of 1000 ppm and 1800 ppm significantly deteriorated the accuracy in performance for all tasks relative to 600 ppm. For the attention task (CPT), the percentages of errors increased significantly during all exposure conditions relative to the base line condition at which the temperature was set at 20°C. For the memory task (MTS), the percentages of errors increased significantly during all exposure conditions relative to the base line condition except during condition 4 at which the temperature was set at 23°C. Lan et al. [12] provided an explanation that different tasks are accomplished by different dominant hemispheres and different brain cortices. After adding thermal comfort sensation votes in the final model, the percentages of errors increased significantly for both tasks when participants perceived the ambient thermal environment as cold, warm and hot. For the attention task, cool and slightly cool thermal sensations attributed to significant lower percentages of errors. This result concurs with the findings of Tham and Willem (2010) [13] that moderate cool exposure can result in higher mental arousal. After adding the variables of the reported symptoms of intolerable thermal discomfort that impairs focusing and other symptoms which impaired the focusing ability like headache, fatigue and dizziness, the percentages of errors increased significantly for both cognitive tasks during all exposure conditions. Zhang et al. [14] indicated that the increase in the intensity of neuro-behavioral symptoms like headache and difficulty in thinking can cause subjects to feel more tired and more sleepy. For the significant fastened performance observed at 23°C and 25°C, Bruyn and Lamoureux [15] provided an explanation for the high speed due to a rise in internal body temperature, which resulted in an increase in the rate of neural activity. The significant slowed performance observed at 20°C could be attributed to the deterioration of dexterity of hands due to stiffening of joints and slow muscular reaction, numbness, and a loss in strength [12].

5. Conclusions

- Decreasing classrooms' temperature from 25°C to 23°C, and also increasing temperature from 20°C to 23°C whilst decreasing CO_2 levels from 1800 ppm and/or 1000 ppm to 600 ppm significantly improved the performance of adult female students in a memory task. Decreasing temperature from 25°C and 23°C to 20°C whilst decreasing CO_2 levels from 1800 ppm and/or 1000 ppm to 600 ppm significantly improved their performance in an attention task.
- Cold, hot and warm sensations can negatively affect mental performance for memory and attention tasks while mild cooling sensation can improve mental alertness.

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Indoor Environmental Quality in Finnish Elementary Schools and Its Effects on Students' Health and Learning

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Indoor Environmental Quality in Finnish Elementary Schools and Its Effects on Students' Health and Learning

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ABSTRACT

The aims were to assess indoor environmental quality (IEQ) in Finnish elementary school buildings, and to study associations between ventilation rate and student health and learning outcomes. The study population consisted of about one thousand sixth grade students from 59 schools in southern Finland. Students' learning outcomes were assessed based on mathematics test scores as a part of a national assessment program. In addition, students (with the help of their parents) responded to a questionnaire about their health. Indoor environmental quality in classrooms was assessed by on-site measurements of ventilation rates and temperatures. Background information of school building was collected from the Finnish register centre. Based on the measurements, mean ventilation rate per student was 3.0, 3.0 and 6.5 L/s/student for schools with natural, mechanical exhaust, and mechanical supply and exhaust ventilation systems, respectively. Mean temperature was 22.4^{0}C.There was no significant correlation between measured IEQ (ventilation and temperature) and school level health and learning outcomes in this sample of schools. In conclusion, mean ventilation rate per student did not meet building code regulations in naturally ventilated schools and schools with mechanical exhaust only. Mean temperature was within the recommended range. Relatively small number of schools limits the conclusions about the associations between IEQ, health, and learning. More detailed analyses including multi-level analyses and non-linear modeling is required for more definite conclusions.

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ABBREVIATIONS

^0C	Degree Celsius
AHU	Air Handling Unit
AQ	Air Quality
ASHRAE	American Society of Heating, Refrigeration, and Air Conditioning Engineers
BRI	Building-Related Illness
FNBE	Finish National Board of Education
FPRC	Finnish Population Register Centre
HVAC	Heating, Ventilation, and Air Conditioning
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
MVOCs	Microbial Volatile Organic Compounds
NBCF	National building code of Finland
PAH	Polycyclic Aromatic Hydrocarbon
PAQ	Poor Air Quality
POM	Particle bound Organic Matter
SBS	Sick Building Syndrome
SD	Standard Deviation
SPOF	State Provincial Offices of Finland
U.S.A	United States of America
US EPA	United States Environmental Protection Agency
VOCs	Volatile Organic Compounds
WHO	World Health Organization

Contents

1 INTRODUCTION

Most children spend majority of their time indoors. In Finland, up to eight hours can be spent in school for a period of five days (Monday to Friday), which make children to get exposed to any contaminant present in the air they breathe. Indoor environmental quality (IEQ) is influenced by outdoor environmental quality and also pollutants generated indoors. There have been a few studies done on schools' indoor environment when compared to that of other buildings such as offices and industrial buildings, even though children, unlike adults are more susceptible to air pollution and they cannot make decision about their school environment (Wargocki and Wyon, 2006). Children are more susceptible to pollutants present in the air than adult, because their tissues and organs are immature and continue to rapidly develop, and they breathe higher volumes of air relative to their body weights (Mendell and Heath, 2005 and Cartieaux *et al.,* 2011). Environmental problems may be more common in school building than in other buildings due to low funding for operation and maintenance of facilities (Mendell and Heath, 2005).

Different studies carried out show that school classrooms can be polluted by various indoor pollutants, which includes molds, bacteria, allergens, particles, volatile organic compounds (VOCs), and formaldehyde (Zhao *et al*., 2008). Ventilation is an important factor affecting IEQ of buildings. Mechanical ventilation may reduce the amount of pollutants entering indoor from outdoor while the concentration of outdoor pollutants that enter indoor environment is close to unity when direct ventilation is used (Chen *et al.,* 2011).

The state of different school buildings may have effect on their IEQ. An old school building may have its ventilation systems not performing at the optimal level, whereas a new building or a recently renovated school building may have a modern mechanical ventilation system that will reduce the amount of pollutants from outdoor to the minimum. The material for building construction may vary due to the year of construction and availability of funds for construction. Old school buildings may be constructed with materials that will affect IEQ, for example, asbestos and lead (Flynn *et al*., 2000). Old school buildings may also have less insulation and leakier structures, thus more exposed to cold (Espejord, 2000).

According to Nandasena *et al.,* (2010) ‘Exposure to air pollutants is related to a variety of health effects, depending on the type of pollutant, amount of the pollutant exposed to, duration and frequency of exposure, and associated toxicity of the specific pollutant’. Health effects that can be caused or exacerbated by indoor environmental pollutants in children include breathing difficulties, asthma and allergies, pneumonia and other respiratory infections, lower respiratory symptoms, etc. This in turn may result in decrease performance due to health issues or may require intermittent absenteeism from school. Eide *et al.* (2010) concluded that ‘Children with poor health have lower educational attainment, lower social status, worse adult health outcomes, and a higher likelihood of engaging in risky behaviors than their healthy peers’.

This study was conducted as a part of large research project on Indoor Environmental Quality and Academic Performance in Schools (Haverinen-Shaughnessy et al. 2012). This work is focused on studying associations between IEQ in schools and group level health and learning outcomes among 6th grade students in Finland.

2 Review of the literature

2.1 Interacting factors of IEQ

IEQ is affected by various interacting factors, including building occupants, climate, building construction (original design or later modification during renovation) and mechanical systems, construction techniques and contaminant sources (e.g. excess moisture and microbial growth, processes and activities within the building, building and furnishing materials, and outdoor sources) (US EPA., 2010). Human activities that affect IEQ in schools includes body odour, cosmetic odour, housekeeping activities (dust and dirt from the air, house cleaning materials, emission from trash and store supplies), those from building system includes materials from damaged asbestos, chemicals released from building components or furnishing e.g. volatile organic carbons or inorganic carbons, HVAC system problems that results in dirt and dust in ductwork or other components, refrigerant leaks and improper venting, and outdoor contaminants (fumes from vehicle exhaust, pollen from plants, etc.) (US EPA., 2010).

2.2 Components of the Indoor Environment

IEQ is an interplay between physical, chemical and biological factors (Table 1). Biological contaminants include allergens from animal dander, dust mites, moulds and bacteria, while chemical contaminants comes from combustion products e.g. environmental tobacco smoke, residue from biomass burning (particulate matters), gases (CO_2, CO, SO_2,NO_x, O_3, NH_3) and off-gassing emissions e.g. formaldehyde and VOCs (Dales *et al.,* 2008). The physical factors of indoor environment can have direct effect on building occupants, modify body’s response to indoor pollutants, and can interact with indoor pollutants (Levin, 1995). These include air temperature, pressure, humidity, and air movement. Table 1 shows different indoor environmental factors and Figure 1 illustrates different components affecting IEQ.

Table 1. Different physical, chemical, biological and particle factors that affect IEQ.

	Indoor Environmental Quality		
Physical factors	Chemical factors	Biological factors	Particulate matter
Temperature Humidity Air pressure, Air movement (draught) Lighting Noise Cleanliness	(Organic) VOCs, PAH e.g. Benzo[a]pyrene, Formaldehyde (Inorganic) CO_2, CO, SO_2,NO_x, O_3, NH_3, Radon (Odours)	Moulds (fungi) Bacteria Plant pollen Dust mites Animal dander	Dust Tobacco smoke Fibres (e.g. asbestos) Combustion by-products

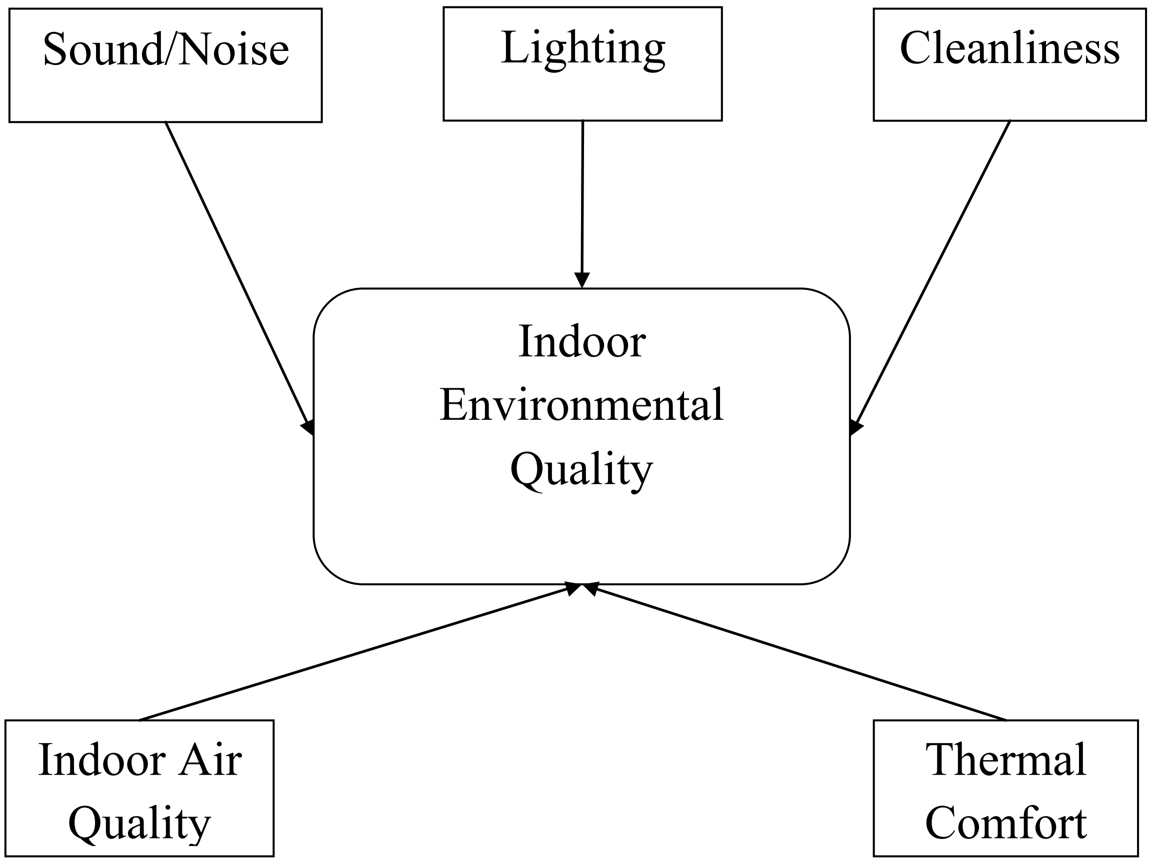

Figure 1. Different components affecting IEQ

2.3 IEQ and Ventilation

Ventilation is the process of replacing noxious air in space with fresh air. Pasanen (1998) defines ventilation as the process of supplying or removing conditioned or non-conditioned air by natural or mechanical means to or from any space. It involves the exchange of indoor air to the outside and even circulation of air within a building. This helps to remove excessive moisture, odour and contaminants as well as introducing outside air so as to prevent the stagnation of indoor air. Ventilation can be done mechanically by the use of air handling unit (AHU) which manipulates outside air that will go indoor by removing contaminants present, or naturally. Natural ventilation can be maximised by opening windows for outside air to enter indoor freely. Different types of mechanical ventilation systems include 1) mechanical exhaust ventilation system, in which a centrally placed fans continually extracts the right amount of air from the indoor environment, and 2) mechanical supply and exhaust ventilation where centrally located fans continually introduce and extract the right amount of air from the indoor environment (WHO, 2009).

A recent review conducted in the U.S.A on indoor air, ventilation, and health symptoms in schools strongly suggest that many classrooms are inadequately ventilated leading to health symptoms (Daisey *et al.,* 2003). Sundell *et al.,* (2011) reported that a lower ventilation rate is associated with inflammation, respiratory functions, asthma symptoms, and short-term sick leave while there is a reduction in allergic conditions among children of Nordic countries when ventilation rates is above 0.5 air change per hour. A study that investigated 10 naturally ventilated schools in Shanghai, China, concluded that asthma symptoms in pupils were caused by outdoor air pollution from traffic (Mi *et al.,* 2006). Ventilation system may also be a source of odorous and stuffy air (Pasanen *et al*., 1995). Ventilation rate per student has been assigned a reference value of 6l/s per student in Finland since 1987 (Ministry of Environment and Palonen *et al*., 2009). In general, poor building designs, as well as poor maintenance of heating, ventilation and air conditioning systems can result in insufficient ventilation of classrooms (Shendell *et al.,* 2004a).

2.4 IEQ and Health

Indoor air have been shown to contain contaminants that at an increased concentration can exacerbate pre-existing health conditions such as asthma, or cause a health condition such as cough to occur (Flynn *et al*., 2000). The contaminants in indoor air vary from biological to chemical contaminants. Bacterial, moulds, VOCs, particle bound organic matter (POM), and micro particles have been reported and confirmed to cause health problems in school children (Cartieaux *et al.,* 2011). Biological contaminants (e.g. moulds, dust mites, cockroaches) can exacerbate pre-existing asthma (Dales *et al.,* 2008).

Exposure to chemical contaminants as well as environmental tobacco smoke can adversely affect lung function in children (Dales *et al.,* 2008). Microbial Volatile Organic Compounds (MVOCs) and plasticizers in school environment may pose a risk factor for asthmatic symptoms in children (Kim *et al.,* 2007). Lack of thermal comfort in school is associated with headaches, drowsiness, and eye and upper airways discomfort (Andersen and Gyntelberg, 2011).

2.5 IEQ and Building Condition

Different building types may have different IEQ characteristics, which could be partly attributed to building age and construction materials. For example, old school buildings may have asbestos in them, and ventilation system may be old, and can be of natural type. Some 77% of 39 Swedish schools that were measured for building code regulations did not meet the requirements (Wargocki *et al.,* 2005).

School buildings are commonly in need of extensive repairs. Some 63% of U.S.A students, corresponding to about 14 million students, attended schools with substandard building (Mendell and Heath, 2005). A Swedish study that investigated eight primary schools found high levels of MVOCs and plasticizer in new buildings as a result of emissions from building materials (Kim *et al.,* 2007). Sick building syndrome (SBS) is commonly reported in school buildings. SBS describe situations in which building occupants experience acute health effects that appear to be linked to time spent in building (Saijo *et al.,* 2010 and Zhang *et al.,* 2011). SBS can also occur in newly built buildings (Saijo *et al.,* 2011).

Building-related illnesses (BRI) include cough, fever, and allergic disease, which often require prolonged recovery time and can become chronic to an individual. BRI are described as clinically verifiable diseases with symptoms that persist even after the occupant leaves the building. Seltzer (1994) listed four mechanisms by which illness can be induced by BRI agent. They include (1) immunologic, (2) infectious, (3) toxic, or (4) irritant. Some agents may work through more than one mechanism.

2.6 IEQ and Thermal Comfort

Thermal comfort is a state of mind in which a person is satisfied with the thermal environment; it is a result of the body's heat exchange with the environment (ASHRAE standard 55, 2004 and Van Hoof *et al*., 2010). It adds to a person's total environmental contentment, welfare, and performance (Van hoof, 2008).
It has been estimated that to achieve thermal comfort for eighty-five percent of building dwellers, indoor temperature should be lower than 24^0C (Andersen and Gyntelberg, 2011).

Air temperature, radiant temperature, humidity and air speed as well as clothing and metabolic rate influences thermal comfort (ASHRAE standard 55, 2004).

People feel more comfortable in air conditioned rooms. Naturally ventilated buildings in China could not meet ASHRAE standard 55 that stipulates criteria of 80% acceptability (Yang and Zhang, 2007). A thermal study that uses 0.7 clo uniform on 36 school pupils of each gender show that indoor temperature should not exceed 23^0C (Andersen and Gyntelberg, 2011). A pilot study on portable classrooms suggested that there was no provision for comfort for occupants in the classrooms (Shendell *et al.,* 2004a). Increasing air exchange may improve thermal comfort and air quality (Cartieaux *et al.,* 2011).

2.7 IEQ and Student Academic Performance

There are limited studies on IEQ and its effect on student performance (Shendell *et al.,* 2004b). Relationships between IEQ, student health, attendance, and performance have been demonstrated in some studies (Shendell *et al.,* 2004b). In a study by Wargocki and Wyon (2006), poor air quality and high temperature had a negative effect on students' performance. A preliminary study carried out in U.S.A found a significant association between inadequate ventilation and student academic performance (Shaughnessy *et al.,* 2006). In a later study, substandard ventilation in classrooms was found to have a linear relationship with student academic performance (Haverinen-Shaughnessy *et al.,* 2011). There is a beneficial effect of improved ventilation on student's academic performance (Bakó-Biró *et al.,* 2007).

A 2011 eye witness report on modern indoor climate research in Denmark states that moderate heat stress reduces mental performance and learning of school children (Andersen and Gyntelberg, 2011). Thermal discomfort in school is associated with reduced attention, concentration, productivity, and comfort (Langiano *et al.,* 2008). A review of indoor pollutant attributed an adverse influence of poor IEQ on attendance and performance of students through health outcomes (Mendell and Heath, 2005). IEQ factors can affect students performance by affecting teachers health which results in sick-leave or non effective teaching (Mendell and Heath, 2005). When classroom conditions improve; student performance improves (Wargocki et al., 2005).

2.8 Schools, IEQ and health in Finland

There are about 3300 schools (primary and secondary) in Finland with approximately 578, 000 students (Palonen *et al.,* 2009). Moisture and mould damage in Finnish school buildings has been reported as a cause of health symptoms in pupils (Meklin *et al.,* 2002 and Patovirta *et al.,* 2004). A clinical study of Finnish pupils found a relationship between mould damaged school and asthma in students (Taskinen *et al.,* 1997). Remediation of moisture damage has reduced health symptoms prevalence in Finnish school buildings (Haverinen-Shaughnessy *et al.,* 2004 and Meklin *et al.,* 2005).

A Finnish study of 10 schools with 56 classrooms conducted in the 1990's found an average ventilation rate in classrooms to be 3.5L/s or 1.2L/s per square meter (Palonen *et al.,* 2009). Between 25-30% of 108 classrooms in 60 schools studied in Southern Finland were in crucial need of replacement or repair of their ventilation system and ventilation was inadequate in majority of the classrooms (Palonen *et al.,* 2009). The National building code of Finland gives the current ventilation standard of 6l/s per student or 3l/s per m^2 (Kurnitski, 2007).

Palonen *et al.,* (2009) and Kurnitski, (2007) affirmed that an improved Finnish classroom ventilation rate of about 10L/s per person coupled with a better thermal comfort will increase the speed of students to perform classroom tasks.

Putus *et al.,* (2004) found an association between chemical and microbial indoor air contaminants in a school building in Finland, and adverse effects such as asthmatic symptoms, respiratory irritation, eyes symptoms and prevalence of common viral respiratory infection. However, no relationship existed between the exposures and doctor diagnosed asthma, other allergic diseases and bacterial respiratory disease. Health symptoms have also been related to IEQ among Finnish school teachers (Patovirta *et al.,* 2004 and Haverinen-Shaughnessy *et al.,* 2007).

3 AIMS OF THE STUDY

The general aim of this work is to study the associations between IEQ in schools and pupils' learning outcomes in Finland. It also aims to study the effects of classrooms IEQ on students' health. The specific aims were:

- To determine if the average ventilation rate per student, ventilation rate per m^2 and temperature is in agreement with that stipulated in the building code regulations.
- To investigate if the age of the school building correlated with classroom indoor temperature and ventilation rate per student.
- To investigate correlation between number of student in a classroom and ventilation rate per student.
- To investigate if ventilation rate in school is associated with students' learning outcomes.
- To investigate if health symptoms of students are associated with their classroom conditions.

4 MATERIAL AND METHODS

4.1 Data from the Finish register

Southern Finland elementary schools and sixth grade students were studied in this research. There are 2802 Finish elementary schools with 3749 buildings, but Finnish Population Register Centre (FPRC) database had information on 3514 buildings. This information includes year of construction, type of heating, type of ventilation, floor area, structure type, and construction materials.

To get the above information, data from all buildings classified as building for ``education`` (N=7562) were reviewed. Elementary schools in Finland were identified with name and address by using the listings and matching data from the Finish National Board of Education (FNBE) and the State Provincial Offices of Finland (SPOF).

The difference between total elementary school buildings and those gotten from FPRC database were due to inaccurate information or missing data. The FPRC data provide the exact locations (coordinates) of the buildings: they were used in Map search for verification and matching the schools with corresponding building sites.

A total of 59 schools from Southern Finland were included in the field measurements. Figure 2 shows the map of Finland (ArcMap 9.1) with geographic distribution of Finnish elementary schools, while Figure 3 shows the map of Finland with geographic distribution of Southern Finland elementary schools studied.

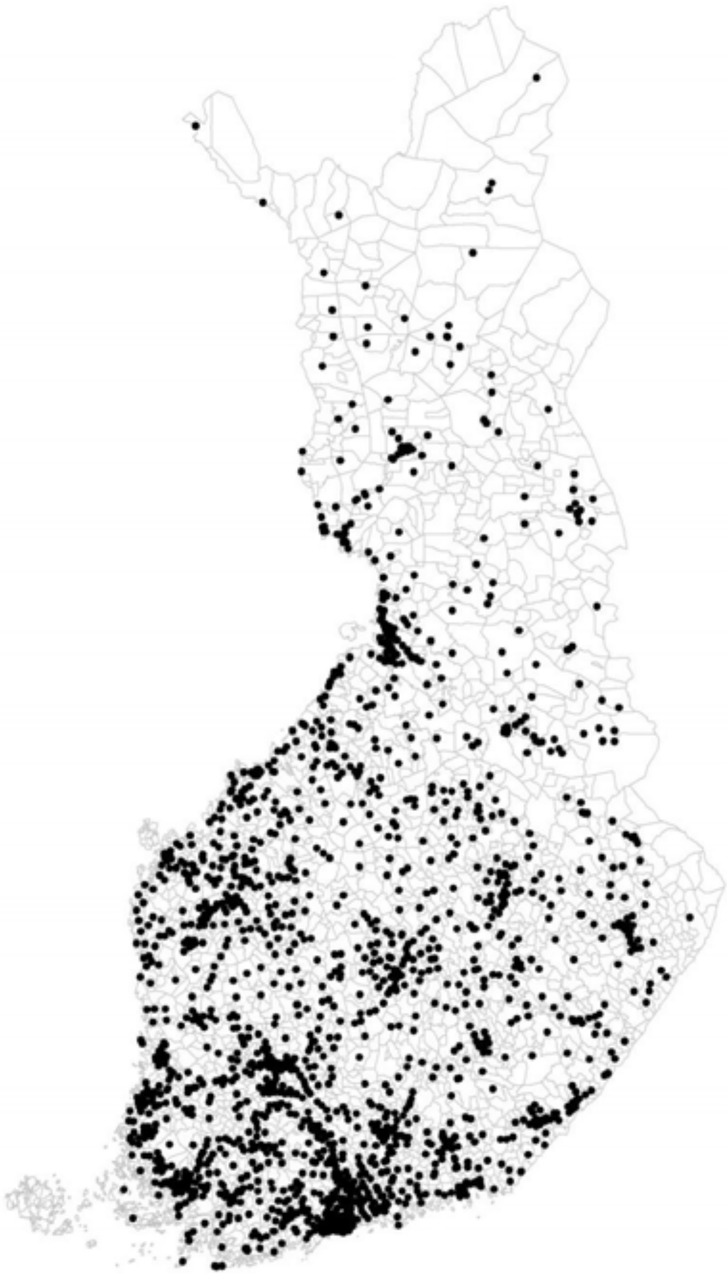

Figure 2. Geographic distribution of Finnish elementary schools (Figure prepared with ESRI ArcMAP 9.1 by Ari Paanala based on spatial information collected from schools, 2012)

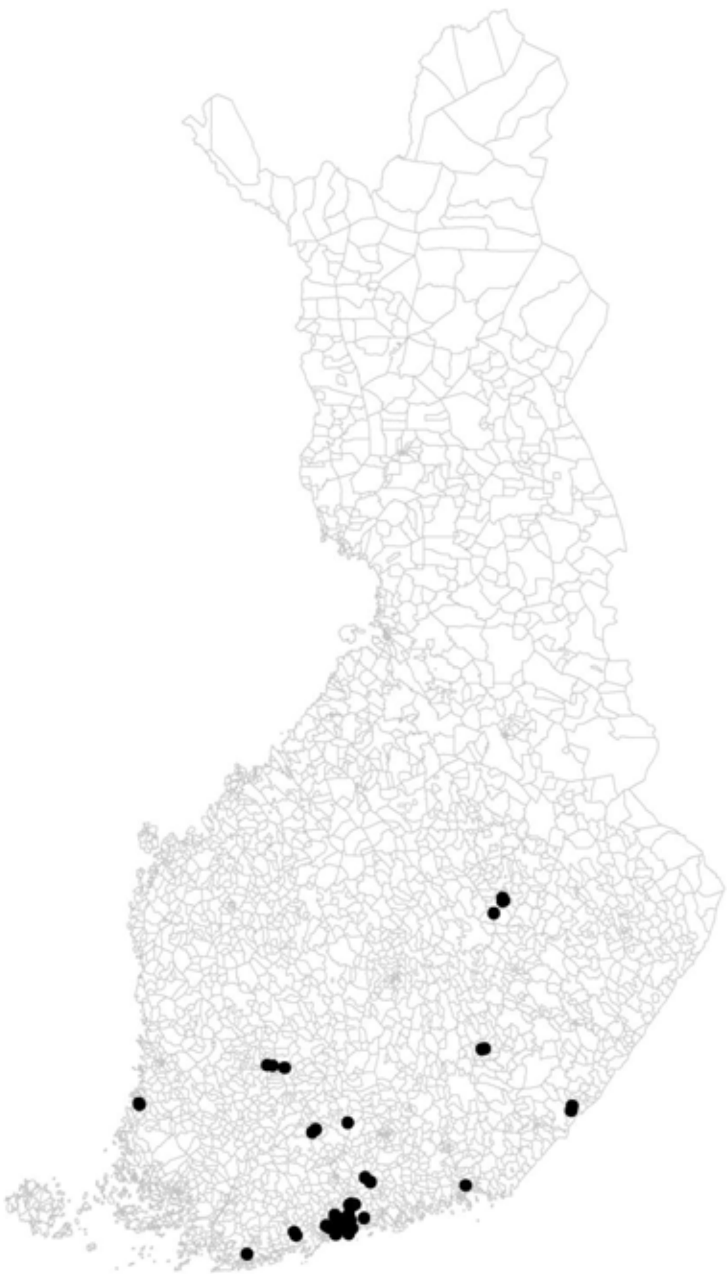

Figure 3. Geographic distribution of sampled Southern Finland elementary schools (Figure prepared with ESRI ArcMAP 9.1 by Ari Paanala based on spatial information collected from schools, 2012)

4.2 Data concerning the learning outcomes

Learning outcomes were assessed based on mathematics tests performance of students. Students' gender, first language, and test performance were taken into consideration. Stratified random sampling was used to collect data about learning outcomes from the pupils (Niemi, 2007). The overall percentage of correct answers was used as the main measure of mathematics achievement.

4.3 Data from health questionnaire

Health questionnaires were sent to school offices and were distributed by school teaching personnel to the sixth grade students, who attended the schools sampled for learning outcome assessment. (This was done after the completion of learning assessment in the schools sampled). The questionnaire could also be filled online (internet) through the project website. The questionnaires were to be filled by the students with the help of their parents. The questions asked were based on social economic status (6 questions), students' health and well being (18 questions), home environment (6 questions), one question on school environment, four questions on living habits (e.g. eating and sleeping), and two questions on learning (advantages or disadvantages), making a total of 37 questions.

For confidentiality reasons, manual matching of health questionnaire was done with mathematics test results. Students that answered anonymously to the health questionnaire could not be matched.

4.4 Physical Measurement

On site investigation was done in the spring and summer of 2007. A total of 107 classrooms from 59 schools assessed for learning outcomes were investigated. Data were collected by interviewing maintenance personnel, studying of school blueprint and walk-through utilizing pre-designed check-lists. Ventilation systems were examined and sixth grade classrooms were selected for ventilation rate measurement based on exhaust air flow or CO_2 measurement.

CO_2 levels were measured for a period of 5-10 days for classrooms with passive stack ventilation system while for classrooms with mechanical exhaust ventilation, exhaust air flow were measured from exhaust air vents in the classrooms. Room temperatures were measured from the same selected classrooms for several weeks using data-loggers. The number of sixth grade students in the measured classrooms with math score was 2130, the number of student that filled the health questionnaire was 1054, and 997 students had both math test and questionnaire response.

4.5 Data Analysis

PASW (Predictive Analytics Software) Statistics, version 18 was used to analyze all the data collected. The descriptive statistics including mean, minimum, maximum and standard deviation for continuous variables were calculated.

Majority of the data collected were not normally distributed, therefore non-parametric method of correlations (Spearman's rho) was used for measured variables and those from FPRC.

Factor analysis was performed on the measured parameters for variable reduction purposes. The analysis was based on Eigen values greater than 1, using Varimax rotation. Also, independent sample median test and independent samples Mann – Whitney U test were used to check for differences between non normally distributed samples that were divided into two groups (required and not required), while independent samples T-test was used for normally distributed samples.

5 RESULTS

5.1 Measurements from school building

A total of 107 sixth grade classrooms from 59 Southern Finland schools were assessed for number of students, ventilation, temperature, construction, renovation, airflow, etc. Information about the schools studied such as year of construction, floor area, number of floors and time of HVAC upgrade were received from FPRC. Out of the 59 schools assessed, the newest was constructed in 2001 while the oldest school was constructed in 1875. The latest HVAC upgrade was done in 2006. However, not all schools were upgraded; in that case the age of ventilation system corresponds with the year of construction. Table 2 outlined the descriptive statistics (mean, median, standard deviation, minimum and maximum) of various parameters received from (FPRC).

Table 2. Descriptive statistics of school buildings from Finnish register.

Attribute	Mean	Median	SD	Min.	Max
Year constructed	1967	1971	23.8	1875	2001
Floor area (m^2)	3115.5	3413.5	2060.4	100.0	8730.0
Number of floors	1.9	2.0	0.9	1.0	4.0
Volume (m^3)	12742.7	13460.0	8438.8	600.0	36677.0
HVAC upgrade (year)	1986	1998	22.4	1914	2006

On-site measurements included number of students, classroom height, area, airflow or CO_2 measurements, and temperature measurements. Based on the measurements, ventilation rates per meter square, ventilation rates per student, mean temperature, as well as minimum and maximum temperature were calculated. The mean (min – max) number of students in a sixth grade classroom was approximately 24.0 (8 - 47), ventilation per student (L/s/student) was 5.7 (1.0 – 20.0), class room height was 319.5 cm (265.0 cm-385.0 cm). Table 3 gives the descriptive statistics (mean, median, standard deviation, minimum and maximum) of the various parameters.

Table 3. Descriptive statistics of classroom parameters measured.

Attribute	Mean	Median	SD	Min.	Max
Number of students	24.0	24.0	5.3	8.0	47.0
Area (m^2)	61.0	60.0	9.2	40.0	99.0
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)	2.1	1.9	1.1	0.5	5.0
Ventilation per student (L/s/student)	5.7	4.7	3.8	1.0	20.0
Mean temperature (^{0}C)	22.4	22.3	1.0	20.4	24.5
Max temp (^{0}C)	23.7	23.5	1.2	21.4	28.3
Min temp (^{0}C)	21.2	21.2	1.1	18.7	23.5

Factor analysis was performed on all the school parameters (from Finnish register and those measured); the rotated component matrix is shown in Table 4. Five components were extracted, clustering variables related to 1) ventilation, 2) temperature, 3) classroom dimensions, 4) floor area, number of students and ventilation per student and 5) size and age of the building. One variable (marked bold) from each component was selected for further analyses: Ventilation per student, mean temperature, floor area, number of students and year of construction.

Table 4. Varimax rotated component matrix

	Component				
	1	2	3	4	5
Ventilation/m^2	.941				
Airflow measurement	.928				
Ventilation per student	**.865**			-.310	
HVAC upgrade	.638				
Minimum temperature		.938			
Mean temperature		**.922**			
Maximum temperature		.736			
Volume			.963		
Floor area			**.944**		
No of floors			.537		.487
Area				.895	
Number of students				**.867**	
Year constructed					**-.888**
Height					.736

Spearman's rho correlations for selected parameters are shown in Table 5.

The number of students in a classroom correlated significantly with ventilation per student. Ventilation per student correlated with number of students inside classroom, and mean temperature. Mean temperature correlated with ventilation per student. Year of construction and floor area did not correlate significantly with any of the parameters chosen. Table 16 in the appendix shows the correlations between all school buildings parameters.

Table 5. Correlations: Spearman's rho.

	N	No. of student	Ventilation/ student	Mean Temp.	Year of construction	Floor area
No. of student	107	1.000	-.359**	-.063	-.162	.181
Ventilation/ student	105	-.359**	1.000	-.303**	.217	-.233
Mean Temp.	95	-.063	-.303**	1.000	.042	-.107
Year of construction	59	-.162	.217	.042	1.000	-.173
Floor area	6	.181	-.233	-.107	-.173	1.000

(N = Number of classrooms studied, ** shows significant correlation)

5.2 Information about the students

Information about students' backgrounds, including age, gender, and home factors (exposure to pets, mould, house location, etc.), were analysed and presented in Table 6.

Table 6. Students' background.

Attribute	Mean	Median	SD	Min.	Max
Age	12.5	12.5	0.1	12.3	13.0
Gender (% of boys)	46.8	48.9	12.4	21.1	74.3
% students that have pet currently	69.6	69.2	12.4	42.3	94.4
% students that had pet earlier	14.9	15.0	9.5	0	50.0
% with furry animals	15.2	13.0	9.4	1.0	58.0
% exposed to ETS in home	0.9	1.0	9.4	0	4.0
% moisture damage in current home	1.3	1.0	1.3	0	7.0
% mould in current home	0.3	0.0	0.7	0	3.0
% stuffiness or mould odour in current home	0.6	0.0	1.2	0	6.0
% live in city center	10.9	3.3	17.1	0	71.4
% live in suburb	64.4	84.2	37.2	0	100.0
% live in fringe area	10.1	.0	20.9	0	85.7
% live in densely populated area	14.6	.0	26.9	0	100.0
% live in apartment building	29.5	28.6	27.4	0	84.3
% live in a row house	15.2	12.5	12.9	0	100.0
% live in a family house or duplex	53.0	54.2	29.8	0	100.0
% live in a farm	2.3	.0	7.6	0	41.2
% mother has a university degree	23.8	25.0	14.0	0	57.1
% father has university degree	22.7	20.0	15.1	0	54.5
mean hours sleep per night	8.8	8.9	0.3	7.8	9.3
% take naps regularly	0.4	0.0	1.5	0	6.3
% eats breakfast daily	87.0	89.3	10.2	50.0	100.0
% eats breakfast twice a week	6.5	5.6	7.2	0	30.0
% exercise 3 times a week	65.3	66.7	13.7	25.0	100.0
% need personal tutoring	8.9	7.4	7.7	0	31.6
% first language Finnish	96.2	100.0	6.3	77.9	100.0
% first language Swedish	.30	.0	1.7	.0	11.1
% other language	3.5	0.0	6.0	.0	22.2
number of students that responded to health questionnaire	24.0	20.0	15.3	2.0	88.0
% correct answers in math test (mean)	62.9	63.8	8.6	37.3	75.5

The school background of the students was also analysed. The number of year spent in current school, percentage missed school days, mean days missed and IEQ factors causing discomfort for the students are shown in Table 7.

Table 7. Students' school background.

Attribute	Mean	Median	SD	Min.	Max
years in current school	5.2	5.3	0.5	3.6	6.0
% missed school days	53.1	52.6	13.5	17.6	100.0
number of days missed, mean	3.6	3.4	1.3	1.8	8.0
% too high temp. in classroom weekly	7.0	4.7	9.8	0	50.0
% too high temp. in classroom daily	2.8	0	4.1	0	14.3
% too low temp. in classroom weekly	1.3	0	2.8	0	10.5
% too low temp. in classroom daily	0.7	0	2.1	0	10.5
% stuffy air or poor IAQ weekly	22.3	16.7	17.8	0	73.5
% stuffy air or poor IAQ daily	9.4	6.2	10.9	0	50.0
% mould odour weekly	1.2	0	3.6	0	20.5
% other unpleasant odour weekly	4.7	2.9	6.0	0	28.6
% noise weekly	32.8	29.1	20.4	0	100.0
% dust weekly	7.7	7.0	7.2	0	31.3
% mould odour daily	0.3	0	1.6	0	10.3
% other unpleasant odour daily	2.2	0	3.6	0	14.3
% noise daily	19.1	14.3	18.8	0	100.0
% dust daily	2.7	0	4.8	0	25.0

Selected health outcomes, collected by a questionnaire, were analysed statistically and presented in Table 8.

Table 8. Students' health status

Attribute	Mean	Median	SD	Min.	Max
% weekly stuffy nose	9.8	10.0	6.8	0	33.3
% weekly rhinitis	5.5	5.3	5.0	0	17.6
% weekly sore throat	2.0	0	3.3	0	11.1
% weekly dry cough	1.9	0	2.9	0	10.5
% weekly wheezing	0.8	0	2.6	0	16.7
% weekly eye symptom	3.1	0	4.2	0	16.7
% weekly fever	0.7	0	1.7	0	6.7
%weekly backpain	1.7	0	3.0	0	11.8
% weekly fatigue	9.0	8.3	7.0	0	33.3
% weekly headache	6.5	4.3	7.1	0	33.3
% weekly difficulties in concentration	3.3	0	4.4	0	16.7
% symptoms associated with school	3.0	3.0	0	0	3.0
% asthma	8.0	6.0	6.3	0	22.2
% allergic rhinitis	21.2	20.0	10.1	0	50.0
% dysphasia	0.9	0	2.3	0	11.1
% dyslexia	0.1	0	0.6	0	3.7
% ADHD	0.7	0	1.7	0	5.6

5.3 Relationship between measured IEQ and student perceived IEQ

Pupils' responses to perceived environment factors (including too high or too low temperature in classroom, poor air quality (PAQ), noise, and dust/lack of cleanliness) were analysed together with the measured data extracted by factor analysis from Table 4 (mean temperature, and ventilation per student). The results are presented in Table 9.

Mean temperature had significant correlation with self-reported poor air quality daily and dust weekly, while ventilation per student correlated with self-reported poor air quality daily. Table 16 (in the appendix) show complete bivariate correlations between all the variables.

Table 9. Correlations: Spearman's rho.

	% too high temp.in class weekly	% too high temp.in class daily	% too low temp.in class weekly	% too low temp.in class daily	Poor air quality weekly	Poor air quality daily	noise weekly	noise daily	Dust weekly	Dust daily
Mean temp	.197	.165	-.046	.008	.215	.409**	-.073	-.135	.285*	.238
Vent./ student	-.060	-.201	.027	-.251	-.197	-.300**	.103	-.118	-.153	-.115

5.4 Correlation between IEQ and student health

The level of correlation was analyzed between measured indoor environmental quality indicators and pupils' health status. No significant correlation existed between any of the variables analyzed as shown in Table 10.

Table 10. Correlations: Spearman's rho.

	Ventilation per student	Ventilation per m^2	Mean temp.	Maximum temp.	Minimum temp.
General health status (poor)	-.136	-.100	.247	.205	.237
Mean days missed	-.088	-.069	.157	.139	.066
Missed school days due to respiratory infections	.047	.025	.024	-.021	-.037
Weekly fatigue	-.122	-.132	.054	.105	.060
Weekly headache	-.148	-.156	.231	.259	.258
Weekly difficulties in concentration	-.073	-.115	-.066	-.052	-.010
Asthma	.178	.169	.190	.144	.166

5.5 Correlation between IEQ and student academic performance

Ventilation and temperature measurements were also analyzed with students' learning outcomes by finding the level of correlation using non-parametric (Spearman's rho) correlation. The result as shown in Table 11 depicts no significant correlation between the measured IEQ and students' learning outcomes.

Table 11. Correlations: Spearman's rho

	Ventilation per student	Ventilation per m^2	Mean temp.	Maximum temp.	Minimum temp.
Learning outcomes	-.015	-.066	.016	.069	.086

5.6 Ventilation rate per student and ventilation per m^2 with different ventilation types.

In the 107 classrooms from 59 schools investigated, 78.5% had mechanical supply and exhaust ventilation type (84 classrooms), 17 classrooms (15.9%) had natural type of ventilation, while only 6 classrooms (5.6%) had mechanical exhaust ventilation system only. Table 12 and Table 13 show descriptive statistics for ventilation rate per student and ventilation rate per m^2 for each of the ventilation type respectively. The mean ventilation rate per student was 3.0, 3.0 and 6.5 L/s/student for schools with natural, mechanical exhaust, and mechanical supply and exhaust ventilation systems, respectively while the mean ventilation per m^2 was 1.1, 1.2 and 2.4 L/s/m^2 in the same order.

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Table 12. Ventilation rate per student for different ventilation type

	Ventilation per student (L/s per student)			
Ventilation type	Mean	S.D	Minimum	Maximum
Natural	3.0	.9	1.8	4.7
Mechanical exhaust	3.0	1.8	1.0	4.6
Mechanical supply and exhaust	6.5	3.9	1.2	20.0

Table 13. Ventilation rate per m^2 for different ventilation type

	Ventilation per m^2 ($L/s/m^2$)			
Ventilation type	Mean	S.D	Minimum	Maximum
Natural	1.1	.3	.7	1.5
Mechanical exhaust	1.2	.6	.5	1.7
Mechanical supply and exhaust	2.4	1.1	.5	5.0

5.7 Reference ventilation per student, learning outcomes and health outcomes

Ventilation per student in schools was divided into 2 categories: 1) those with ventilation rate 6 L/s per student and more, and 2) those with less than 6 L/s per student. Analyses from the 54 schools measured show that 31 (57.4%) schools have lower than required ventilation rate per student (i.e. 6 L/s per student). The mean (min – max) test score was 63.8 (37.7 – 75.5) % in group 1 and 62.3 (37.3 – 74.7) % in group 2. Independent sample median test and Independent samples Mann – Whitney U test show that the difference is not statistically significant (p values 1.000 and 0.448 respectively).

There was also no significant difference between selected health outcomes (poor general health status, mean days missed, missed school days due to respiratory infections, weekly fatigue, weekly headache, weekly difficulties in concentration, and asthma) between schools with lower ventilation rate per student and those with required ventilation rate per student when Independent samples median and Independent samples Mann – Whitney U test were used to analysed them. The p - values are shown in Tables 13 and 14 respectively for Independent samples median test and Independent samples Mann – Whitney U test respectively.

Table 14. Hypothesis test summary (Independent samples median test)

	Null hypothesis	p - value	Decision
1	The medians of poor general health status are the same across categories of ventilation per student (high or low).	.395	Retain the null hypothesis
2	The medians of mean days missed are the same across categories of ventilation per student (high or low).	.659	Retain the null hypothesis
3	The medians of missed school days due to respiratory infections are the same across categories of ventilation per student (high or low).	.501	Retain the null hypothesis
4	The medians of weekly fatigue are the same across categories of ventilation per student (high or low).	.659	Retain the null hypothesis
5	The medians of weekly headache are the same across categories of ventilation per student (high or low).	.318	Retain the null hypothesis
6	The medians of weekly difficulties in concentration are the same across categories of ventilation per student (high or low).	.442	Retain the null hypothesis
7	The medians of asthma are the same across categories of ventilation per student (high or low).	.501	Retain the null hypothesis

Table 15. Hypothesis test summary (Independent samples Mann – Whitney U Test)

	Null hypothesis	p - value	Decision
1	The distribution of poor general health status is the same across categories of ventilation per student (high or low).	.400	Retain the null hypothesis
2	The distribution of mean days missed is the same across categories of ventilation per student (high or low).	.828	Retain the null hypothesis
3	The distribution of missed school days due to respiratory infections is the same across categories of ventilation per student (high or low).	.255	Retain the null hypothesis
4	The distribution of weekly fatigue is the same across categories of ventilation per student (high or low).	.786	Retain the null hypothesis
5	The distribution of weekly headache is the same across categories of ventilation per student (high or low).	.326	Retain the null hypothesis
6	The distribution of weekly difficulties in concentration is the same across categories of ventilation per student (high or low).	.446	Retain the null hypothesis
7	The distribution of asthma is the same across categories of ventilation per student (high or low).	.556	Retain the null hypothesis

5.8 Reference temperature, learning outcomes and health outcomes

Mean temperature in schools was also divided into two categories of those having the required indoor mean temperature of 23^0C and lower and those with above 23^0C that is considered as thermal discomfort. Out of 51 schools assessed, 38 (74.5%) schools had a mean temperature of 23^0C and lower, while 13 (25.5%) schools had a higher mean temperature. Mean temperature was normally distributed according to Shapiro-Wilk test. Therefore Independent samples t-test was used to analyse the difference between mean temperature with learning outcomes and health outcomes. There was no significant difference between learning outcomes of students in school with thermal comfort and those without it (p value = 0.637).

There was also no significant difference between selected health outcomes: poor general health status ($p = 0.101$), mean days missed ($p = 0.595$), missed school days due to respiratory infections ($p = 0.529$), weekly fatigue ($p = 0.520$), weekly headache ($p = 0.090$), weekly difficulties in concentration ($p = 0.936$), and asthma ($p = 0.648$) of student in schools with required thermal comfort and those with higher mean temperature.

6 DISCUSSION

The study population consisted of about one thousand sixth grade students from 59 schools in southern Finland. The maximum age of the students studied was 13 years with mean age of 12 years and 6 months. A child normally starts schooling (grade 1) at the age of 7 years in Finland (FNBE). There were about the same number of boys and girls studied (47% boys and 53% girls), with majority of them studying in the same school since grade 1. This is a normal practice in Finland, where students change school mainly due to family relocation.

The average number of student in the classrooms studied was 24. The mean (319.5cm), minimum (265cm) and maximum height (385cm) of the classrooms conform to national building code of Finland (NBCF) regulations which stipulate the minimum height of a habitable room to be 250cm (Ministry of Environment). Classroom net area also exceeds the minimum area for a habitable room of $7m^2$ in the national building code (Ministry of Environment).

Airflow measurement (L/s) shows that the design was working below performance (Kurnitski, 2007). Although the observed difference was not further analysed, there exists a difference of 38.5 (L/s) between the mean of airflow design and its current performance. This may be as a result of lack of maintenance of ventilating apparatus or aged equipments (Palonen *et al*., 2009). This may result to lower ventilation than needed in the classrooms, and could cause a reduction in the quality of air indoors. Based on the ventilation capacity of the HVAC system, a lower performance from the design will result to a reduction in ventilation per m^2 and also ventilation per student.

The total average ventilation rate per student (5.7 L/s per student) was lower than the required 6 L/s per student according to NBCF (Ministry of Environment, Palonen *et al*., 2009 and Kurnitski, 2007). A total of 31 schools have less than 6 L/s per student ventilation rate. Mean ventilation per m^2 (2.1 L/s per m^2) also fall short of the standard (3 L/s per m^2) of NBCF (Kurnitski, 2007). When the ventilation rate per student and ventilation rate per m^2 was analysed based on the type of ventilation (natural, mechanical exhaust and mechanical supply and exhaust), natural ventilation and mechanical exhaust ventilation had lower than required ventilation rate per student of 3.0 L/s per student each, while mechanical supply and exhaust air ventilated classrooms had a ventilation rate of 6.5 L/s per student which conforms with NBCF regulation for ventilation rate per student. Ventilation rate per m^2 was also higher for mechanical supply and exhaust ventilation system when compared to the other two types but none of them met the requirement of 3 $L/s/m^2$ of NBCF (Kurnitski, 2007). Also Bornehag et al., (2005) reported that buildings with mechanical supply and exhaust ventilation system had a higher ventilation rates than those with natural and mechanical exhaust ventilation. There were few classrooms using natural ventilation and mechanical exhaust ventilation (6 and 17 respectively) when compared to those using mechanical supply and exhaust air ventilation (84 classrooms), which may have effect on the data analysis.

Mean temperature in classroom (22.4 ^{0}C) was within the requirement of 23 ^{0}C or lower and majority of the schools studied (74.5%) met the requirement (Andersen and Gyntelberg, 2011).

A negative correlation existed between number of student in a classroom and ventilation per student. It means that when the number of student in a classroom increases, the amount of ventilation to individual student decreases and vice versa. It appears that the number of students in a classroom should not be too high so as to give way for adequate ventilation of the classrooms. An inverse correlation between mean temperature and ventilation per student also show that a high classroom temperature may be related to reduced ventilation rate and vice versa. There was very little or no effect of floor area on ventilation per student, mean temperature, and number of students in a classroom because there was no significant correlation between it and the IEQ parameters mentioned. The negative correlation (-.233) it had with ventilation per student (although not statistically significant) means that a smaller classroom size is related to higher ventilation rate per student. A bigger classroom will likely have a large number of students in it, which may correspond to lower ventilation rate per student unless the air flow is adjusted for the number of students.

Year of construction had no significant correlation with ventilation rate per student, mean temperature and number of students in a classroom but there exist a positive non significant correlation of .217 with ventilation rate per student. Ventilation system type has been changed over time from the initial natural ventilation to mechanical exhaust and more recently to mechanical supply and exhaust ventilation, which has been shown to provide better ventilation (Bornehag et al., 2005).

Mean temperature measured had a significant positive correlation with student perceived poor air quality daily and dust weekly. An increase in classroom indoor temperature therefore has an effect on perceived IAQ and this supports earlier works done in this regard (Ashrae standard 55, 2004, Shaughnessy *et al*., 2006 and Yang and Zhang, 2007). Ventilation rate per student had an inverse significant correlation with poor air quality daily. This may be as a result of insufficient amount of outdoor air entering classroom as well as HVAC systems not performing well due to lack of proper maintenance already reported by Palonen *et al.,* (2009). There was also a negative correlation (-.251) between ventilation rate per student and student perceived too high temperature in the classroom daily. This further supports the claim that reduced ventilation rate may be related to high classroom temperature as already stated above.

Although there was no significant correlation between IEQ indicators and pupils' health outcomes, mean, maximum, and minimum temperature had some positive correlation with poor health status, weekly headache, and asthma. Ventilation rate per student and ventilation rate per m^2 also showed some positive correlation with asthma. This depicts that when the mentioned IEQ parameters increases, the selected health status may also increase among the student (Daisey *et al.,* 2003 and Sundell *et al.,* 2011).

The result of no significant correlation found between IEQ and learning outcomes established that IEQ had very little effect on the group level performance of the students studied.

Although the mean, minimum, and maximum scores were all higher for students in schools with the required ventilation rate per student of 6 L/s per student and higher when compared to those from schools with a lower than required ventilation rate per student, there was no statistically significant differences between the two groups. Also, the comparisons of students' health and learning outcomes based on whether indoor temperature met the requirement or not showed that the outcomes were not different among the groups of students in schools with the required indoor temperature and those whose indoor temperature was not up to requirement. There was a p-value of 0.09 for weekly headache; a larger school sample may show that thermal discomfort in schools can result to headache for students.

7 CONCLUSIONS

Based on the result, the following conclusions can be drawn;

- The average ventilation rate per student did not meet building code regulations in naturally ventilated schools and schools with mechanical exhaust only. The mean temperature was within the recommended range.

- The age of the school building did not correlate with classroom indoor temperature and ventilation rate per student. There is need for efficient ventilation in order to meet the building code requirement.

- Ventilation rate per student decreases as the number of students in a classroom increases. Ventilation rates should therefore be adjusted for the maximum number of student in a classroom.

- No statistically significant correlation was observed between ventilation rate and students' learning outcomes.

- Relatively small number of schools limits the conclusions about the associations between IEQ, health, and learning. More detailed analyses including multi-level analyses and non-linear modeling is required for more definite conclusions.

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9 Appendix

9.1 Table 16. Correlations between measured variables and those from FPRC

	N	No. of student	Ventilation/ student	Area	Height	Air Flow Measurement	Ventilation Measurement	Ventilation/m2	Mean Temp.	Min. Temp.	Max. Temp	Year of construction	HVAC upgrade	No. of floors	Floor area	Volume
No. of student	107	1.000	-.359**	.276**	-.001	-.031	.117	-.110	-.063	-.239*	.025	-.162	-.183	.148	.181	.204
Ventilation/ student	105	-.359**	1.000	-.207*	-.307**	.926**	-.944**	.944**	-.303**	-.080	-.370**	.217	.703**	-.313*	-.233	-.225
Area	107	.276**	-.207*	1.000	.050	-.100	.245*	-.262**	.153	.062	.153	-.174	-.184	-.042	-.050	-.026
Height	107	-.001	-.307**	.050	1.000	-.297**	.401**	-.304**	.159	.085	.186	-.474**	-.409**	.286*	.209	.238
Air Flow Measurement	105	-.031	.926**	-.100	-.297**	1.000	-.967**	.971**	-.313**	-.137	-.359**	.146	.709**	-.262*	-.192	-.166
Ventilation Measurement	105	.117	-.944**	.245*	.401**	-.967**	1.000	-.991**	.339**	.143	.386**	-.246	-.739	.254	.167	.140
Ventilation/m2	105	-.110	.944**	-.262**	-.304**	.971**	-.991**	1.000	-.350**	-.160	-.390**	.211	.714**	-.248	-.152	-.131
Mean Temp.	95	-.063	-.303**	.153	.159	-.313**	.339**	-.350**	1.000	.862**	.881**	.042	-.249*	.019	-.107	-.175
Min. Temp	95	-.239*	-.080	.062	.085	-.137	.143	-.160	.862**	1.000	.631**	.009	-.058	.092	-.121	-.194
Max. Temp	95	.025	-.370**	.153	.186	-.359**	.386**	-.390**	.881**	.631**	1.000	.083	-.246	-.103	-.171	-.243
Year of construction	59	-.162	.217	-.174	-.474**	.146	-.246	.211	.042	.009	.083	1.000	.224	-.527**	-.173	-.164
HVAC upgrade	70	-.183	.703**	-.184	-.409**	.709**	-.739**	.714**	-.249*	-.058	-.246	.224	1.000	-.234	-.100	-.123
No. of floors	62	.148	-.313*	-.042	.286*	-.262*	.254	-.248	.019	.092	-.103	-.527**	-.234	1.000	.449**	.516**
Floor area	62	.181	-.233	-.050	.209	-.192	.167	-.152	-.107	-.121	-.171	-.173	-.100	.449**	1.000	.949**
Volume	57	.204	-.225	-.026	.238	-.166	.140	-.131	-.175	-.194	-.243	-.164	-.123	.516**	.949**	1.000

9.2 *Table 17.* Relationship between measured IEQ and student perceived IEQ

	Mean temp	Vent./ student	% too high temp.in class weekly	% too high temp.in class daily	% too low temp.in class weekly	% too low temp.in class daily	Poor air quality weekly	Poor air quality daily	noise weekly	noise daily	Dust weekly	Dust daily
Mean temp	1.000	-.350*	.197	.165	-.046	.008	.215	.409**	-.073	-.135	.285*	.238
Vent./ student	-.350*	1.000	-.060	-.201	.027	-.251	-.197	-.300**	.103	-.118	-.153	-.115
% too high temp.in class weekly	.197	-.060	1.000	.745**	-.029	.077	.519**	.559**	.239	.175	.280*	.468**
% too high temp.in class daily	.165	-.201	.745**	1.000	-.060	.051	.427**	.589**	.140	.102	.156	.268
% too low temp.in class weekly	-.046	.027	-.029	-.060	1.000	.700**	.011	.041	.283*	.207	.254	.297*
% too low temp.in class daily	.008	-.251	.077	.051	.700**	1.000	.138	.185	.434**	.424**	.240	.360**
Poor air quality weekly	.215	-.197	.519**	.427**	.011	.138	1.000	.759**	.463**	.442**	.421**	.588**
Poor air quality daily	.409**	-.300*	.559**	.589**	.041	.185	.759**	1.000	.324*	.335*	.514**	.628**
noise weekly	-.073	-.103	.239	.140	.283*	.434**	.463**	.324*	1.000	.862**	.209	.246
noise daily	-.135	-.118	.175	.102	.207	.424**	.442**	.335*	.862**	1.000	.234	.309*
Dust weekly	.285*	-.153	.280*	.156	.254	.240	.421**	.514**	.209	.234	1.000	.695**
Dust daily	.238	-.115	.468**	.268	.297*	.360**	.588**	.628**	.246	.309*	.695**	1.000

RESEARCH ARTICLE

Effects of Classroom Ventilation Rate and Temperature on Students' Test Scores

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Abstract

Using a multilevel approach, we estimated the effects of classroom ventilation rate and temperature on academic achievement. The analysis is based on measurement data from a 70 elementary school district (140 fifth grade classrooms) from Southwestern United States, and student level data (N = 3109) on socioeconomic variables and standardized test scores. There was a statistically significant association between ventilation rates and mathematics scores, and it was stronger when the six classrooms with high ventilation rates that were indicated as outliers were filtered (> 7.1 l/s per person). The association remained significant when prior year test scores were included in the model, resulting in less unexplained variability. Students' mean mathematics scores (average 2286 points) were increased by up to eleven points (0.5%) per each liter per second per person increase in ventilation rate within the range of 0.9–7.1 l/s per person (estimated effect size 74 points). There was an additional increase of 12–13 points per each 1°C decrease in temperature within the observed range of 20–25°C (estimated effect size 67 points). Effects of similar magnitude but higher variability were observed for reading and science scores. In conclusion, maintaining adequate ventilation and thermal comfort in classrooms could significantly improve academic achievement of students.

Significance

We studied relationships between students' test scores and both classroom ventilation rate and temperature. The study is unique, because it utilizes multilevel analyses and a large database, including measured data on ventilation and thermal parameters, and student level data on standardized test scores. Based on the results, maintaining adequate ventilation and thermal comfort could raise an average tests score to "commended performance". The study helps to understand the potential benefits of effectively managing indoor environmental factors in schools.

Introduction

Recent studies have reported associations between provision of ventilation (outdoor air) and students' health and academic performance. For example, one field study from California

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Competing Interests: The authors have declared that no competing interests exist.

found a statistically significant 1.6% reduction in illness absence per each additional liter per second per person (l/s per person) of ventilation provided [1]. Another study from the Southwestern United States estimated that for every l/s per person increase up to 7.1 l/s per person, the percentage of students passing the State's core curriculum based standardized tests could increase by 2.9% (95%CI 0.9–4.8%) in mathematics and 2.7% (0.5–4.9%) in reading [2]. At the same time, these studies reported average ventilation rates of the school systems studied being equal or less than 4 l/s per person, indicating that the majority of schools had ventilation rates below the American Society of Heating, Refrigerating, and Air-Conditioning recommended minimum of 7.1 l/s per person [3]. Also experimental data from Denmark associated increased ventilation rates in classrooms with improved school performance [4]. Low ventilation rates can result in an increased exposure to indoor air pollutants, assumed to be the primary reason for adverse effects on occupant health and performance [5–7].

In addition to inadequate ventilation, some studies have associated elevated indoor temperatures in schools with impaired performance [4, 8]. ASHRAE [9] recommends indoor temperatures in the winter be maintained between 20 and 24°C (68–75°F), whereas summer temperatures should be maintained between 23 and 26°C (73–79°F). These ranges are prescribed acceptable for sedentary or slightly active persons. Both measured ventilation rates and elevated temperatures have been associated with students' self-reported stuffiness or poor indoor air quality in classrooms [10].

The majority of previous studies have been case studies [4] or cross-sectional studies based on school or grade level data on students' background, absenteeism, and performance [2, 11]. At present, we are not aware of previous school effect studies analyzing student level data on performance as well as measured data on ventilation and thermal parameters with multilevel models, which take into consideration the nested structure of the data, i.e. the basic assumption that pupils attending the same school (and classroom) are in some respects more alike than pupils from two different schools (and classrooms). Also the fact that the pupils come from different socioeconomic backgrounds could explain variations in their health and school achievement, which should be taken into account when assessing the amount of variation in pupil outcomes conditioned by differences between schools [12]. Herewith, we report findings from multilevel analyses using linear mixed models (LMM), aiming to study the effects of ventilation and temperature on test scores. The underlying null hypothesis is that students' test scores are not affected by their classroom ventilation rate or temperature.

Materials and Methods

Seventy elementary schools in Southwestern US School district were surveyed and monitored for multiple IEQ parameters during the academic year of 2008–2009. Prior to the data collection, the research project applied and obtained an approval from the school district, with the condition of maintaining the confidentiality of the school district's participation in the study. The area climate is characterized by hot summers (an average of 107 days with maximum temperature $\geq$ 32°C; 90°F) and mild winters (an average of 19 days with minimum temperature below freezing). The average annual temperature is about 20°C (69°F). During the school year, the 5-year average heating degree days is about 946 in°C HDD (1783°F HDD) for base temperature of 18°C (65°F) and cooling degree days is about 530°C CDD (1000°F CDD) for base temperature of 23°C (73°F).

Monitoring of indoor temperature (T), relative humidity (RH), and carbon dioxide (CO_2) was conducted by fourteen TSI QTrak Monitors. The monitors used were calibrated according to the instruction manual and intercalibrated (i.e., compared with each other) weekly. The monitors were rotated on a weekly basis to seven new schools between January 26 and April

18, 2009. In each school, the monitors were deployed in two separate 5th grade classrooms on a Monday morning and picked up on Friday afternoons. Therefore, the continuous data logging lasted a minimum of four days in each classroom. The data loggers recorded data in 5-min increments throughout the days.

Classrooms were monitored under closed conditions, i.e. keeping windows and doors closed as best possible during the occupied hours. Heating, ventilation, and air conditioning (HVAC) systems were operated with fans in the on position during the monitoring period. Recognizing that seasonal times of the year will have some impact on ventilation rates, the closed classroom conditions were instilled to provide an estimate of ventilation rates based on mechanical system introduction of outdoor air.

Preliminary analyses included assessment of indoor T and RH data over a school day, matched with hourly outdoor data obtained from the closest weather station. Average, minimum, and maximum values during the occupied school hours were estimated for each classroom [13]. The following analyses were focused on ventilation rate and average indoor T during the occupied school hours in the classrooms. Ventilation rates for each classroom monitored were estimated from CO_2 data as described by Haverinen-Shaughnessy et al. [2], using a peak-analysis approach based on a mass-balance model [14, 15]. Briefly, since the studied classrooms were 5th grade classrooms and had similar occupant density and activity conditions, the CO_2 generation rate used was 0.0043 l/s per person for students, whereas 0.0052 l/s per person rate was used for teachers [16–18]. The peak-analysis approach assumes that CO_2 concentrations reaches steady state (C_{eq}) in the classrooms. The peak concentration of CO_2 recorded during the measurement period was used as the steady-state value of CO_2.

Other classroom level data included highest degree held by the teacher, which were obtained from the district. In addition, student individual data for 2008–2009 school year were obtained to profile each fifth grade student (N = 3109) in the 70 schools (140 classrooms) related to the student's gender, ethnic background, participation in the free lunch program (commonly used as a socioeconomic indicator), English language proficiency, "gifted" status (i.e. a student who has demonstrated potential abilities of high performance), and mobility rate, as well as data related absenteeism and absenteeism due to illness (corresponding to number of days absent). The information on the students was blinded to the researchers, as it was coded and anonymized.

The district also provided data from the statewide assessment of learning. These data includes students' individual (coded and anonymized) test scores in mathematics, reading, and science from assessment performed in the spring of 2009. In addition, test scores from previous school year (spring 2008) were obtained for mathematics and reading. The annual assessment is designed to relate levels of test performance to the expectations defined in the state-mandated curriculum standards. The state used scale score of 2100 for 'met standard' and 2400 for 'commended performance' for all subject areas.

IBM SPSS statistical package version 21 was used for data analyses. Using linear mixed modelling, the school and classroom or teacher intercept terms were used to account for the dependence among the children at the same school. The model with the random effects (school and classroom or teacher) was used as the zero-model. Final model included random effects and both student and school level variables fitted to the model one by one. The continuous ventilation rate and indoor T variables were centered around their grand means. Since absenteeism and absenteeism due to illness were significantly correlated, a composite variable 'number of days absent, no illness' (i.e. 'total days absent' minus 'number of days absent due to illness') was formed, and the Akaike information criterion (AIC) was used to determine which variables were most suitable for the model. After fitting each variable, the model was studied for within and between subject variance components (as compared to zero-model) and intraclass correlation (ICC), which represents the proportion of total variance that occurs between schools, while the remaining proportion represents variance among students within schools [19]. We also computed the effects of ventilation rate and indoor T on the variance component between schools, to estimate which proportion of the explainable variation in the school mean test scores could be explained by these two factors.

R version 3.1.0 (lme4, LMERConvenienceFunctions, and effects packages) was used to estimate the overall effect size (range) of ventilation rate and indoor T and to illustrate the partial effect of ventilation rate on mathematics score for indoor T below and above the observed mean value. Functions PlotLMER.fnc and effect produce and plot partial effects of a linear-mixed effects-model fitted with lmer (compatible with package lme4).

Results and Discussion

All of the studied classrooms were equipped with locally controlled mechanical HVAC systems. The ventilation systems in 44 schools consisted of single-zone individual room units (i.e., residential style up flow furnace-type systems and side-wall mounted unit ventilators). In addition, 15 schools had fan coil units which were mounted in the individual classrooms for heating and cooling purposes, but no outdoor air provision, and 12 schools had multi-zone air handling units (primarily consisting of rooftop units and central packaged units that would serve two to four classrooms in the building). The multi-zone units would serve classrooms with similar occupant density and occupant activity conditions. While windows could be opened in the majority of the classrooms studied, it was reported that 76% of the classrooms did not open the widows on a daily basis, which was compatible to the district's overriding policy to maintain classrooms with windows closed in order to rely on the mechanical system to temper and condition the air, and to maintain a controlled environment.

The mean classroom level ventilation rate was 3.6, 95%CI 3.2–4.0 l/s per person, and the mean indoor T was 23°C, 95%CI 22.6–22.9°C (73°F, 95%CI 72.6–73.3°F). The mean school level mathematics score was 2286 (95%CI 2258–2313) and the proportion of total variance (ICC) occurring between subjects (school * classroom) was 0.21 (21%). Final multivariate model for mathematics included the following student level variables: gifted status, limited English proficiency, ethnic group, mobility, eligibility to free or reduced lunch, gender, the composite variable 'number of days absent, no illness', as well as teacher's highest degree, and ICC related to this model (not including ventilation rate or indoor T) was 0.10.

After including classroom ventilation rate and indoor T in the final model, ICC decreased to 0.09. Therefore, about 10% of the defined variation in mean mathematics scores between subjects could be explained by ventilation rate and indoor T. Based on the final model, subjects exposed to a difference of 1 l/s per person in ventilation rate differed by 7 (95%CI 1–12) points in mathematics scores; whereas subjects exposed to a difference of 1°C (1.8°F) in indoor T differed by 13 (95% CI 1–26) points, correspondingly (Table 1). The interaction ventilation rate * indoor T was not statistically significant (parameter estimate -3, 95%CI -8-3), possibly due to limited sample size.

Inclusion of previous year's test score did not result in removal of the other variables selected, and it did not change the parameter estimates for ventilation rate (Table 2). This model was better in predicting the mathematics score: the variance component within subjects diminished by 43% and the variance component between subjects diminished by 30%. Many student characteristics and test-taking ability, which could affect each student's test scores, should be accounted for by inclusion of previous year's test scores; however, there remains residual confounding, which could be related to not being able to account for information on unmeasured variables. Such information includes any changes in each individual student's conditions since the previous year's test that could influence his/her performance.

Table 1. Descriptive statistics, parameter estimates for each fixed effect individually, and final model estimates for mathematics score[a].

	N	%	Estimates for each predictor[b] individually			Final model[c]		
	N	**%**	**Estimate**	**(95% CI)**	**Sig**	**Estimate**	**(95% CI)**	**Sig**
Predictors								
Intercept						**3064.9**	**2555.0–3574.7**	**.000**
Gifted status								
No	2811	90.4	-265.8	-(292.6–239.1)	.000	**-228.0**	**-(253.9–202.0)**	**.000**
Yes	298	9.5	0[d]	.	.	**0[d]**	.	.
Limited English Proficiency								
No	2408	77.5	134.9	110.4–159.4	.000	**126.3**	**103.4–149.2**	**.000**
Yes	684	22.0	0[d]	.	.	**0[d]**	.	.
Ethnic group								
Native American	5	0.2	-30.5	-228.3–167.3	.763	**16.0**	**-185.7–217.7**	**.876**
Asian	132	4.2	67.0	21.9–112.2	.004	**66.9**	**23.9–110.0**	**.002**
African American	394	12.7	-201.9	-(233.8–170.0)	.000	**-155.0**	**-(185.4–124.5)**	**.000**
Hispanic	1824	58.7	-129.7	-(153.7–105.7)	.000	**-68.0**	**-(92.0–44.0)**	**.000**
Caucasian	754	24.3	0[d]	.	.	**0[d]**	.	.
Mobility								
Moved to a different district between the fall and spring	232	7.5	-131.7	-(165.7–97.7)	.000	**-98.1**	**-(128.9–67.3)**	**.000**
Moved to a different school between the fall and spring	118	3.8	-90.7	-(134.8–46.6)	.000	**-60.6**	**-(100.6–20.7)**	**.003**
Stayed the whole year	2758	88.7	0[d]	.	.	**0[d]**	.	.
Eligibility to free or reduced lunch								
Free lunch	1696	54.6	-140.5	-(164.2–116.9)	.000	**-52.9**	**-(76.0–29.7)**	**.000**
Reduced lunch	220	7.1	-89.2	-(125.2–53.2)	.000	**-37.0**	**-(70.5–3.6)**	**.030**
Not eligible	1193	38.4	0[d]	.	.	**0[d]**	.	.
Gender								
Male	1597	51.4	-10.2	-26.7–6.2	.223	**1.8**	**-13.1–16.6**	**.813**
Female	1512	48.6	0[d]	.	.	**0[d]**	.	.
Teacher's highest degree								
Bachelor's degree	105	74.5	-19.3	-67.6–29.0	.431	**-31.9**	**-(62.5–1.4)**	**.041**
Master's degree	36	25.5	0[d]	.	.	**0[d]**	.	.
		Mean						
Total days absent	3108	5.9	-4.0	-(5.3–2.6)	.000	**-**		
Days absent due illness	3108	2.2	-0.5	-2.9–2.0	.722	**-**		
Days absent no illness	3108	3.8	-8.1	-(10.1–6.1)	.000	**-6.8**	**-(8.6–4.9)**	**.000**
Ventilation rate[l/s per person]	3092	3.6	19.7	11.4–28.0	.000	**6.7**	**1.0–12.4**	**.022**
Indoor T [°C]	3040	22.7	-32.8	-(51.6–13.9)	.001	**-13.4**	**-(25.9–0.9)**	**.036**

[a] Dependent Variable

[b] added to the zero-model

[c] Includes all predictors

[d] This parameter is set to zero because it is redundant

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Ventilation rates >7.1 l/s per person (i.e. meeting the recommended minimum) exceeded 1.5 times the interquartile range, hence indicated as outliers in the boxplot (Fig 1).

As shown in Table 2, filtering these six classrooms (housing 140 students from five schools), resulted in the parameter estimate for ventilation rate increasing to 11 (95%CI 2–20), whereas the parameter estimate for indoor T did not change considerably. The absolute value of

Table 2. Estimates for ventilation rate and indoor T based on two alternative models[a].

Description of the model		Estimates for each predictor[b] individually			Final model		
Alternative models	**Mean**	**Estimate**	**95% CI**	**Sig**	**Estimate**	**95% CI**	**Sig**
Mathematics score 2007–2008 included[c]							
Mathematics score 2007–2008, N = 2675[d]	2263.5	.9	.8-.0	.000			
Ventilation rate [l/s per person], N = 2661	3.7	19.5	11.0–28.1	.000	**6.7**	**2.0–11.3**	**.006**
Indoor T [°C], N = 2611	22.7	-33.2	-(52.5–13.9)		**-4.2**	**-14.5–6.1**	**.420**
Ventilation rates > 7.1 l/s per person filtered[e]							
Ventilation rate [l/s per person], N = 2951	3.3	36.3	23.7–48.8	.000	**11.2**	**2.0–20.4**	**.017**
Indoor T [°C], N = 2899	22.8	-33.6	-(52.6–14.7)	.001	**-12.0**	**-24.7–0.6**	**.062**

[a] Dependent Variable: Mathematics score

[b] added to the zero-model

[c] Includes previous year's mathematics score added to the models shown in Table 1.

[d] Note: previous year's mathematics score is not available for all students, which could be related to mobility

[e] Final model as in Table 1 (data related to classrooms with ventilation rates > 7.1 l/s per person filtered)

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parameter estimate for interaction increased, but remained non-significant (parameter estimate -4, 95%CI -13-4). The result concurs with a previous study that found a stronger, statistically significant linear association between ventilation rate up to 7.1 l/s per person and the proportion of students passing standardized tests in mathematics [2]. Thus, it appears that the small number of classrooms meeting the recommended minimum ventilation rate increases the uncertainty in the results when schools with higher ventilation rates are included. Corresponding to this model, the estimated effect size (range) for ventilation rate (up to 7.1 l/s per person) was 74 points, and for indoor T it was 64 points. Therefore, these effects combined (138 points) could raise an average tests score (2286 points) to 'commended performance' (>2400 points). Fig 2 illustrates the partial effects of ventilation rate for indoor T below and above the observed mean value.

Further on, we performed stratified analyses for based on the gifted status, English language proficiency, as well as the largest free lunch eligibility categories and ethnic groups (Table 3). With respect to ventilation rate, the final model estimates for the association between mathematics scores were within the whole population standard error (5 points) across different groups, except among the group of African American students, where the estimate was 9 points higher. With respect to indoor T, the estimates were also within the whole population standard error (about 6 points), except among the students with limited English proficiency, where the estimate was 18 points higher, and among the groups of gifted students and African American students, where the associations were positive (higher temperature corresponded with higher test scores) but not statistically significant.

Previous studies have observed differences between Caucasian, Hispanic, and African American students in terms of temperature preference while learning [20, 21], which could indicate possibility for effect modification by ethnic background. However, the sample size in the current study appears limited to further explore this possibility. Further studies are also needed to determine if classroom temperature has a larger effect on students with limited language proficiency.

We also checked if class size (i.e. number of students in the classroom) and school level socioeconomic variables (e.g. percent of student eligible for free lunch) should be included in the models in addition to student-level variables as they have been shown to be important

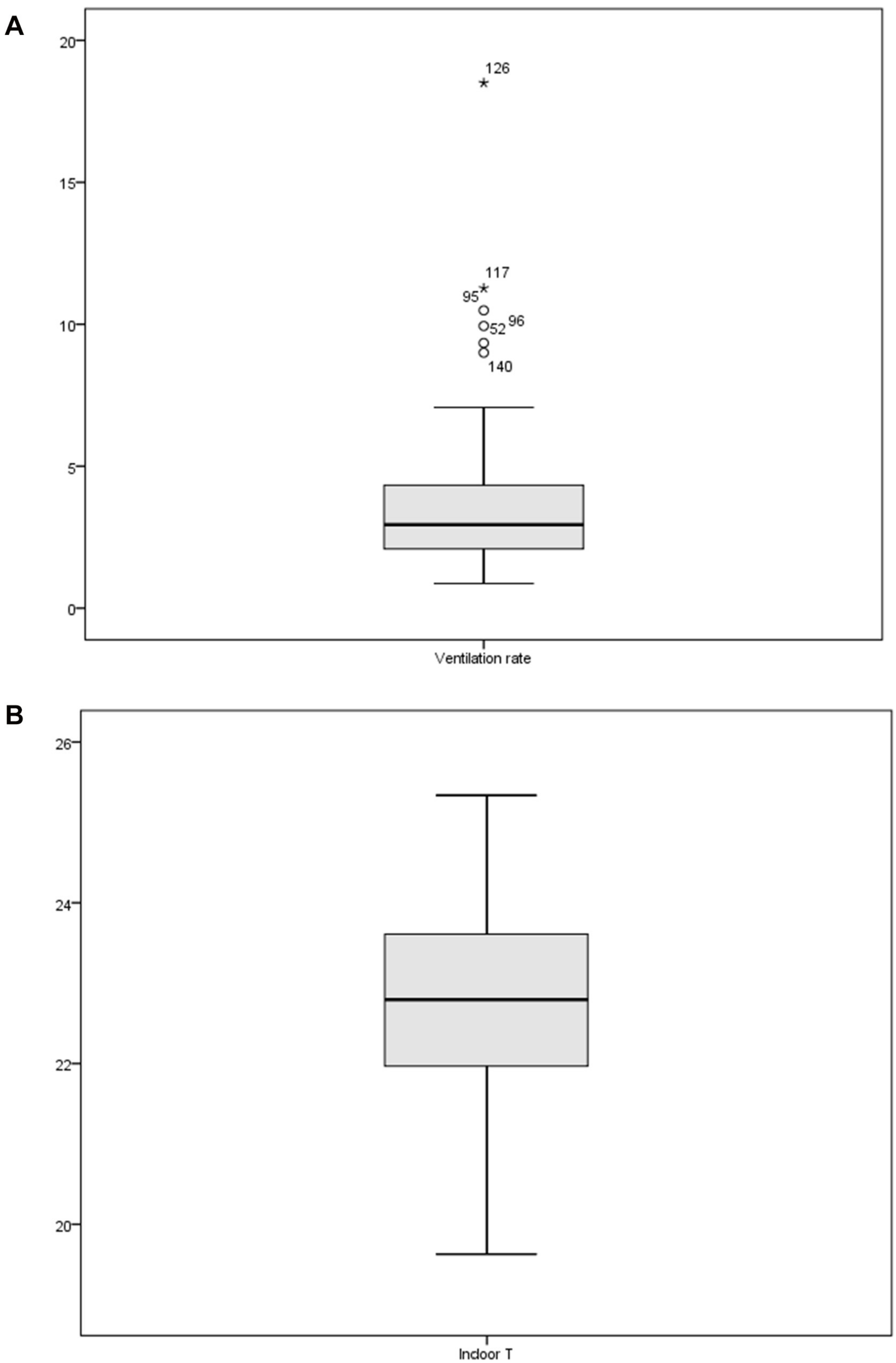

Fig 1. Box plots for ventilation rate [l/s per person] and indoor T [°C]. The outliers are labeled with case numbers.

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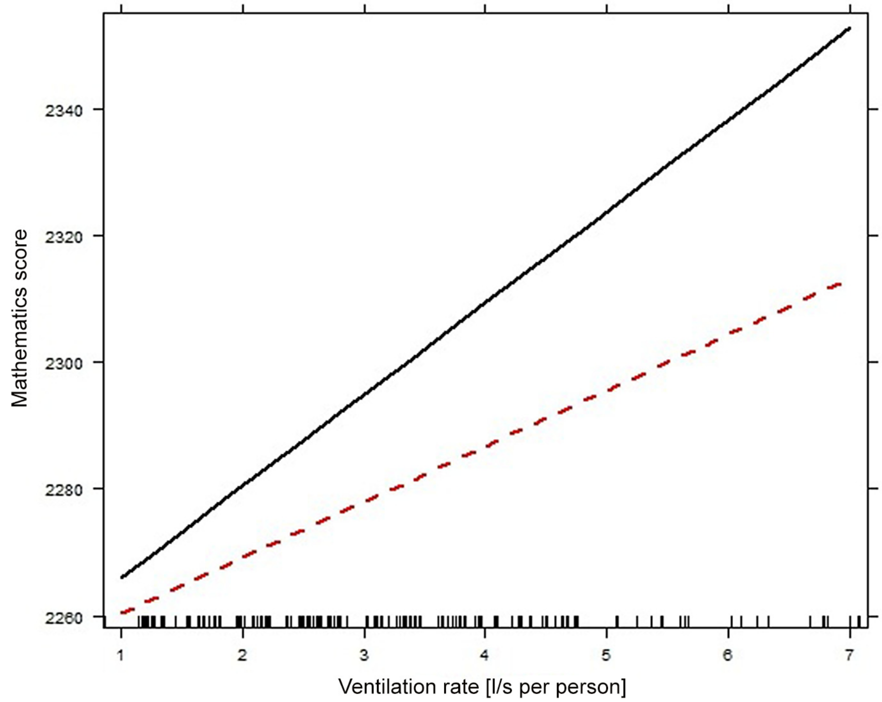

Fig 2. Partial effect of ventilation rate on mathematics score for indoor T below and above 23°C (73°F). Solid line corresponds with indoor T below 23°C (73°F).

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predictors of achievement in previous studies [12, 22]. While these variables did not meet the model selection criteria, we observed significant correlations between school level socioeconomic variables and both ventilation rate and indoor T (data not shown). In addition to making it more difficult to separate the effects of different variables, such correlations may point toward possible inequity issues. Fig 3 shows box plots for ventilation and indoor T by ethnic group and eligibility for free lunch, indicating that on the average, African American and Hispanic students, as well as free lunch eligible were exposed to lower ventilation rates and higher temperatures.

As shown in Table 4, correlations between mathematics, reading, and science scores were high.

The associations between ventilation rate and indoor T and reading and science scores were similar to those related to mathematics scores (Table 5). Yet, adding student level variables to the zero-model for reading reduced ICC from 0.28 to 0.08, after which adding ventilation rate and indoor T did not change it. Adding previous years reading score resulted in ICC decreasing to 0.04, while variance component within subjects diminished by 36% and the variance component between subjects diminished by 69%. Adding student level variables to the zero-model for science reduced ICC from 0.26 to 0.07 and adding ventilation rate and indoor T reduced it further by 8%. There were statistically significant associations between gender and both reading and science: girls achieved higher scores in reading, whereas boys achieved higher scores in science. Teacher's degree did not appear to affect reading scores whereas it associated with both mathematics and science scores.

Overall, ICC between subjects was higher for reading and science than for mathematics, but with respect to reading, inclusion of the student level variables diminished the variance

Table 3. Final model[a] estimates for mathematics score stratified for three largest ethnic groups[b] (Hispanic, Caucasian and African American), eligibility to free lunch[c], gifted status[d], and limited English proficiency[e].

Sample	Whole	Ethnic group			Eligibility to free lunch		Gifted		English	
	population	Hispanic	Caucasian	African American	Free lunch	Not eligible	No	Yes	Limited	Proficient
N	2951	1717	718	382	1633	1109	2811	298	684	2408
	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate
	95%CI	95%CI	95%CI	95%CI	95%CI	95%CI	95%CI	95%CI	95%CI	95%CI
Ventilation rate	11.2*	9.6	11.3	20.4*	6.7	13.8**	11.2*	15.7*	6.4	11.2*
[l/s per person]	2.0–20.4	-2.2–21.4	-0–22.6	2.1–38.7	-6.3–19.7	4.9–22.8	1.6–20.8	2.9–28.5	-12.9–25.8	1.5–20.9
Indoor T [°C]	-12.0	-18.4*	-13.8	7.3	-10.3	-12.7	-12.8	2.9	-30.3*	-7.1
	-24.7–0.6	-(34.1–2.6)	-30.5–2.9	-18.2–32.8	-27.0–6.4	-26.2-.8	-26.0-.5	-15.7–21.5	-(55.7–5.0)	-20.6–6.3

* p < 0.05
**p< 0.01
*** p<0.001
[a] Ventilation rates > 7.1 l/s per person filtered
[b] Final model includes gifted status, limited English proficiency, mobility, eligibility to free or reduced lunch, gender, teachers' highest degree, and days absent no illness
[c] Final model includes gifted status, limited English proficiency, ethnic group, mobility, gender, teachers' highest degree, and days absent no illness
[d] Final model includes limited English proficiency, ethnic group, mobility, eligibility to free or reduced lunch, gender, teachers' highest degree, and days absent no illness
[e] Final model includes gifted status, ethnic group, mobility, eligibility to free or reduced lunch, gender, teachers' highest degree, and days absent no illness

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components more effectively; whereas the school level variables (ventilation rate, indoor T, and teacher's degree) appeared to be more relevant for mathematics and science. The associations between the school level variables and test scores were of similar magnitude. However, it should be noted that many other studies have not found evidence that a master's degree improves teacher skills, attributing the main effects of teacher quality to other characteristics, data not available for this study [22].

In this study, illness absence was not associated with the tests scores. On the contrary, separating non-illness based absence from total days absent resulted in stronger associations, leading to selection of non-illness based absence to the final models. A possible explanation is that motivated students can catch up with their school work after recovering from short-term illnesses. However, other types of absence, which are unlikely related to indoor environmental quality in classrooms, may be more difficult to overcome. These types of absences have been linked to students who will not attend school to avoid bullying, unsafe conditions, harassment and embarrassment, and students who do not attend school because they (or their parents), do not see the value in being there [23]. We also checked if ventilation rates could be associated with illness absence as suggested by Mendell et al. [1], however, we could not confirm this finding. It appears that in these data, the relationship between ventilation rates and test scores is caused by other mechanism(s), such as decreased decision making performance [24], or neurologic symptoms, such as headache, confusion, difficulty thinking, difficulty concentrating, or fatigue [7], and not by increasing illness absence.

It should be noted that this study was conducted all in one grade level and one school district, state, and climate. These restrictions are useful for controlling variability and for increasing precision, but caution is necessary in extrapolating to other types of age groups, school systems, and climates. In addition, the estimates for ventilation rates and temperatures were drawn from a relatively short measurement period. Continuing the study, we collected data

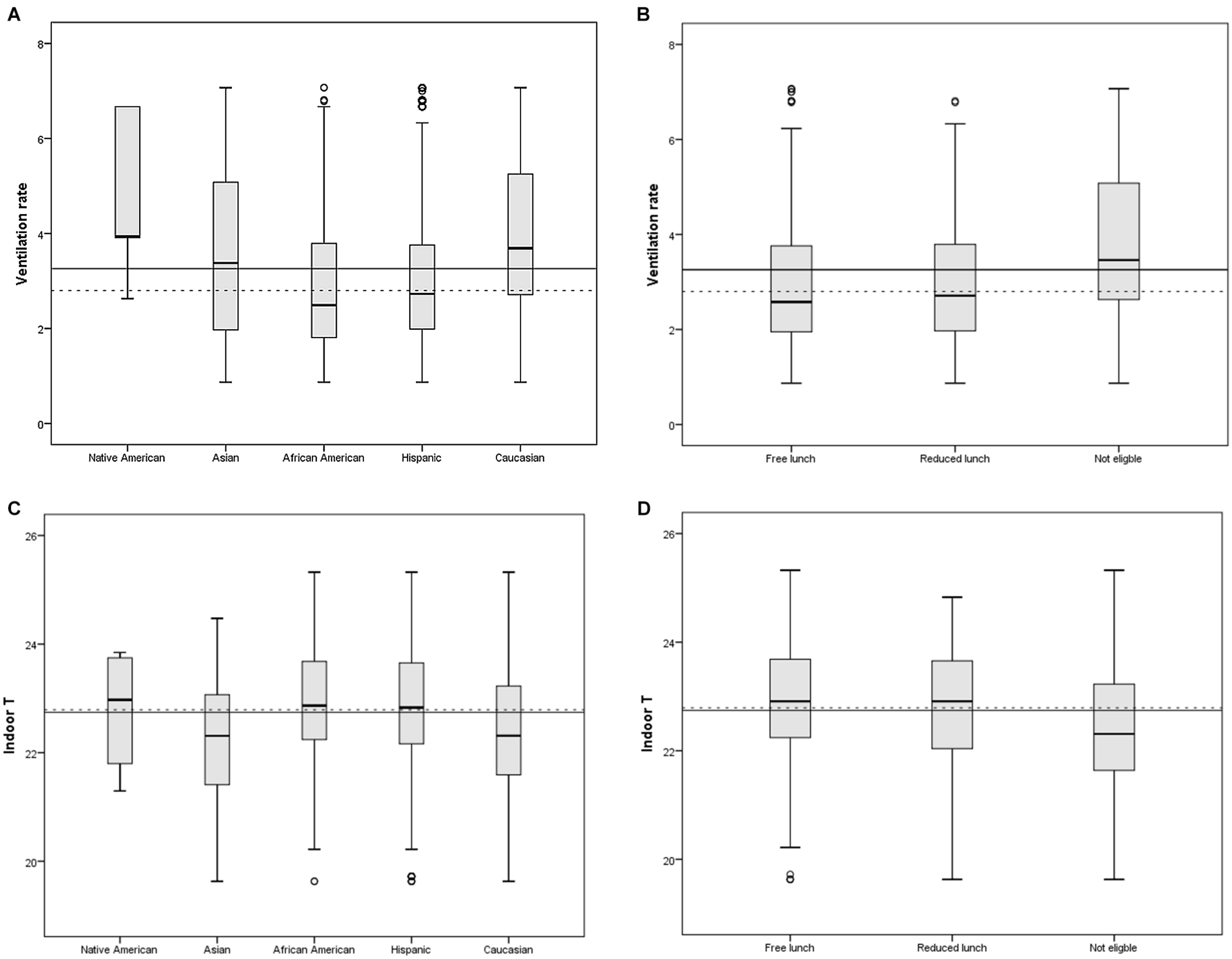

Fig 3. Box plots for ventilation rate [l/s per person] and indoor T [°C] by ethnic group and eligibility for free lunch. Solid line corresponds with population means and dotted line with medians.

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over the following school year in a sub-sample of 27 schools, and observed a high correlation (0.791, $p<0.001$) between ventilation rates estimated based on data in the springs of 2009 and 2010, indicating that the measured ventilation rates in majority of schools could be representative of a long term situation [13].

There exists some uncertainty in the ventilation rate estimates since in many classrooms, the steady state concentrations were not actually attained due to the ventilation rates being so low. In these classrooms, the estimated ventilation rate derived from the peak-analysis approach may reflect an overestimation of the actual ventilation rate. Additional uncertainty is related to the calculation of a CO_2 source generation, which was based on several factors such as age, assumed body weight and surface area, and level of physical activity (light activity). The activity typically varies throughout a school day: higher activity would mean that the actual ventilation rates were lower than the estimated values. On the other hand, windows were asked to be kept closed during the monitoring period, which could result in underestimating the

Table 4. Pearson correlations between test scores.

		Mathematics 2008–2009	Mathematics 2007–2008	Reading 2008–2009	Reading 2007–2008	Science 2008–2009
Mathematics 2008–2009	Pearson Correlation	1	.74**	.64**	.63**	.70**
	N	3017	2653	2977	2645	2984
Mathematics 2007–2008	Pearson Correlation	.74**	1	.62**	.69**	.65**
	N	2653	2675	2629	2642	2636
Reading 2008–2009	Pearson Correlation	.64**	.61**	1	.75**	.68**
	N	2977	2629	2988	2622	2952
Reading 2007–2008	Pearson Correlation	.63**	.69**	.75**	1	.68**
	N	2645	2642	2622	2669	2631
Science 2008–2009	Pearson Correlation	.70**	.65**	.68**	.68**	1
	N	2984	2636	2952	2631	3004

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

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ventilation rate in classrooms with operable windows. In effect, the estimated ventilation rates, while windows were closed, were those afforded by the mechanical system in place. However, it was reported that majority of classrooms were not opening windows on a daily basis. Also considering that the district's policy does not encourage opening windows, the approach used for monitoring with windows closed in this study is most representative.

There were no statistically significant correlations between ventilation rate and average indoor or outdoor T. There was only a weak positive correlation between indoor and outdoor average temperatures (Spearman correlation .243, $p<0.05$), indicating that indoor T is relatively independent on the outdoor conditions, and could be more reflective of the individual school building and its heating and cooling system operation. Including outdoor T in the LMM models did not change the results considerably (data not shown).

With respect to the temperature findings, considering that there are different thermal comfort envelopes for different seasons, it appears that the schools fulfilled the recommendations. The observed associations would indicate that the higher temperatures (for example as specified for summer) might not be ideal for school buildings where students are expected to learn and perform.

Heating, ventilation, and air conditioning are responsible for a large part of school buildings' operation costs as well as their carbon footprint. From both an economic and environmental points of view, schools should strive for optimal HVAC operation to keep energy consumption in check. In support of this premise, US EPA [25] has estimated that a traditional system, upgraded with inclusion of a modern energy recovery ventilation system, can allow for an increased ventilation rate from 2.4 l/s (or 5 cfm) per person to 7.1 l/s (or 15 cfm) per person, with no negative implications in terms of first cost, energy costs, and moisture control.

In conclusion, we could not reject an alternative hypothesis that students' test scores may be affected by their classroom ventilation rate and temperature. Further studies (including interventions) are needed in order to examine the causality of the observed relationships, the residual confounding, and whether the results can be generalized to other climates, building types, and HVAC modes.

Table 5. Final model estimates for fixed effects, reading and science.

Model	Reading score [a]			Science score [a]		
	Final			Final		
Parameter	Estimate	95% CI	Sig	Estimate	95% CI	Sig
Intercept	2762.7	2333.4–3192.0	.000	3011.7	2555.1–3468.2	.000
Gifted status						
No	-173.3	-(195.6–151.0)	.000	-232.3	-(258.0–206.5)	.000
Yes	0[b]	.	.	0[b]	.	.
Limited English Proficiency						
No	114.3	94.7–134.0	.000	151.9	129.6–174.2	.000
Yes	0[b]	.	.	0[b]	.	.
Ethnic group						
Native American	11.4	-160.9–183.8	.897	-120.1	-319.7–79.6	.239
Asian	-32.4	-69.2–4.3	.084	-11.8	-54.2–30.6	.585
African American	-133.0	-(159.2–106.8)	.000	-187.9	-(217.8–157.9)	.000
Hispanic	-85.9	-(106.5–65.3)	.000	-108.5	-(132.2–84.8)	.000
Caucasian	0[b]	.	.	0[b]	.	.
Mobility						
Moved to a different district between the fall and spring	-56.0	-(83.4–28.5)	.000	-59.2	-(89.2–29.3)	.000
Moved to a different school between the fall and spring	-45.0	-(79.3–10.8)	.010	-72.8	-(111.7–34.0)	.000
Stayed the whole year	0[b]	.	.	0[b]	.	.
Eligibility to free or reduced lunch						
Free lunch	-76.4	-(96.2–56.6)	.000	-80.0	-(102.6–57.4)	.000
Reduced lunch	-70.0	-(98.7–41.3)	.000	-67.5	-(100.3–34.6)	.000
Not eligible	0[b]	.	.	0[b]	.	.
Gender						
Male	-27.6	-(40.4–14.9)	.000	44.4	29.6–59.1	.000
Female	0[b]	.	.	0[b]	.	.
Teachers' highest degree						
Bachelor's degree	-9.8	-35.5–15.9	.452	-26.6	-53.9-.8	.057
Master's degree	0[b]	.	.	0[b]	.	.
Days absent no illness	-3.1	-(4.7–1.6)	.000	-4.6	-(6.5–2.8)	.000
Ventilation rate [l/s per person]	4.3	-.5–9.1	.078	4.6	-.5–9.7	.074
Indoor T [°C]	-7.4	-18.0–3.1	.167	-12.4	-(23.5–1.2)	.031
Ventilation rates $\geq$ 7.1 l/s per person filtered						
Ventilation rate [l/s per person]	16.0	8.9–23.1	.000	11.1	3.0–19.1	.008
Indoor T [°C]	-6.5	-16.3–3.2	.189	-11.3	-(22.5-.2)	.046

[a] Dependent variables

[b] This parameter is set to zero because it is redundant

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Author Contributions

Conceived and designed the experiments: UHS RJS. Performed the experiments: UHS RJS. Analyzed the data: UHS RJS. Contributed reagents/materials/analysis tools: UHS RJS. Wrote the paper: UHS RJS.

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CARBON DIOXIDE LEVELS AND DYNAMICS IN ELEMENTARY SCHOOLS: RESULTS OF THE TESIAS STUDY

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ABSTRACT
The Texas Elementary School Indoor Air Study (TESIAS) involved several phases, including single-day continuous monitoring of carbon dioxide (CO_2) in 120 randomly selected classrooms in two school districts. The median time-averaged and peak CO_2 concentrations were 1,286 ppm and 2,062 ppm, respectively. The time-averaged CO_2 concentration exceeded 1,000 ppm in 66% of the classrooms. The peak CO_2 concentration exceeded 1,000 ppm in 88% of the classrooms and 3,000 ppm in 21% of the classrooms. Mean and peak occupied CO_2 concentrations were statistically different ($\alpha = 0.05$) between the two districts, and peak CO_2 concentrations were statistically greater in classrooms that employed packaged terminal air conditioning (PTAC) systems. Statistically significant differences in both mean time-averaged and peak CO_2 concentrations were not observed for portable vs. traditional classrooms, classrooms with outside vs. inside entries, or when data were separated amongst teacher responses to questions related to classroom odors.

INDEX TERMS
Carbon dioxide, Elementary schools, Measurement, Questionnaire

INTRODUCTION
The U.S. General Accounting Office (1995) estimated that one in five U.S. schools has significant indoor air quality (IAQ) problems, a troublesome assessment given that children spend approximately 7,000 hours in classrooms between the levels of K-5 (kindergarten through 5th grade). Daisey and Angell (1999) reviewed over 450 publications related to IAQ in schools, and concluded that many classrooms are not adequately ventilated. Inadequate ventilation can lead to an accumulation of bio-effluents from room occupants, and various gaseous and particulate pollutants associated with building materials, classroom activities, and general housekeeping. For cost savings, many schools have opted to reduce fresh (ventilation) air provided to classrooms, and/or to reduce the frequency of ventilation system maintenance (Casey *et al*., 1995). In some cases, student occupancy of classrooms significantly exceeds that for which the classroom was designed.

Carbon dioxide (CO_2) is often used as a surrogate for evaluation of the adequacy of classroom ventilation, particularly as related to the dilution of pollutants emitted from human metabolic activity (Casey *et al*., 1995; Daisey and Angell, 1999; Smedje and Norback, 1999). Levels of CO_2 greater than 1,000 ppm (or 700 ppm above outdoor background) are generally assumed to be indicative of inadequate ventilation.

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Daisey and Angell (1999) reported that CO_2 concentrations were often > 1,000 ppm in portable classrooms with no outdoor intake or with ventilation systems switched off. Amongst 44 NIOSH Health Hazard Evaluation Reports, 32% of classrooms were reported to have CO_2 concentrations > 1,000 ppm. Smedje and Norback (1999) studied CO_2 in 181 classrooms in 40 schools in Uppsala, Sweden. They observed CO_2 concentrations > 1,000 ppm in 40% of classrooms, with a median CO_2 concentration of 950 ppm.

In this paper we present data related to recent monitoring for CO_2 in 115 elementary school classrooms in Texas. Data were collected as part of a larger Texas Elementary School Indoor Air Study (TESIAS), for which data analysis continues at the time of this writing.

METHODS

Two school districts agreed to participate in the TESIAS study. District B is located in the Rio Grande Valley of Texas, along the Texas-Mexico border. District G is located in Central Texas. The study was limited to elementary schools in each district. Thirty schools were randomly selected, 10 in District B and 20 in District G.

Approximately 1,350 staff (900 teachers) in the 30 participating schools completed a questionnaire intended to better understand staff personal characteristics, the nature of classroom environments (water damage, use of candles in classroom, etc.), detection and type of odors, perceived environmental quality of rooms, and health symptoms amongst staff and their students. In this paper we consider only the question of whether teachers are bothered/irritated by odors in their classroom.

A total of 120 classrooms (40 in District B and 80 in District G) were randomly selected for further analysis from amongst the approximate 900 classrooms in which a teacher had submitted a questionnaire. For each of these classrooms, CO_2, CO, relative humidity, and temperature were monitored over the course of one day. All classrooms in District B were monitored between October 23rd and December 1st, 2000. All classrooms in District G were monitored between November 8th, 2000 and January 14th, 2001.

Real-time, non-dispersive infrared CO_2 analyzers with data-loggers were placed in classrooms approximately 15 to 30 minutes prior to student/staff occupation in the morning. The analyzers were switched off approximately 30 minutes or more after students and teaching staff vacated classrooms at the end of the day. Care was taken to place analyzers approximately 0.8 to 1.2 m above the floor and 1 m from walls, and in locations that would not be directly impacted by the breath of individual children. Anecdotally, data were lost for five of the 120 classrooms by inquisitive students who tampered with the instruments, as evidenced by sharp spikes in CO_2 concentration (from student breath) immediately prior to the cessation of data recording. Analyzers were calibrated using zero and 1,000 ppm span gases in accordance with manufacturer specifications. Outdoor CO_2 concentrations varied from 340 to 410 ppm over the entire study.

A detailed visual survey was made of each classroom, including information related to classroom dimensions, operability of windows, and more. A detailed analysis of the type and nature of HVAC systems that served each classroom was also completed.

In this paper we have presented cumulative distribution plots for time-averaged and peak CO_2 concentrations. Time-averaged values are based on the comprehensive data set, i.e., including times when students were not in the classroom. Actual mean CO_2 concentrations during student occupation were higher. However, the period of data logging before the start, and after the end, of the school day were short and generally had less affect on the mean CO_2 concentration than did lunchtime vacancy of classrooms. Hypothesis testing was completed on the equality of mean and peak CO_2 concentrations ($\alpha = 0.05$; variances unknown and not necessarily equal).

RESULTS

For illustrative purposes, example CO_2 profiles for three classrooms are presented in Figure 1. In each case, t = 0 corresponds to the start of data logging and not student occupation. Variations in CO_2 concentrations are a function of activities that required students to vacate the room, sometimes with the door open and sometimes with the door closed during vacancy. For example, students in CR-1 engaged in a 45-minute physical education period (outside of room) shortly after initial room occupancy and left the room for lunch period from approximately t = 260 to 290 minutes. For classrooms (CR) 1, 2, and 3, the mean time-averaged CO_2 concentrations were 1,180 ppm, 1,653 ppm, and 2,857 ppm, respectively. Peak concentrations were 1,828 (CR-1), 2,570 (CR-2), and 3,337 (CR-3) ppm. A summary of time-averaged and peak CO_2 concentration statistics for all 115 classrooms is presented in Table 1. Statistics are also provided for the 36 and 79 classrooms in Districts B and G, respectively, for which data were successfully logged. Cumulative distribution plots for time-averaged and peak CO_2 concentrations are presented in Figure 2.

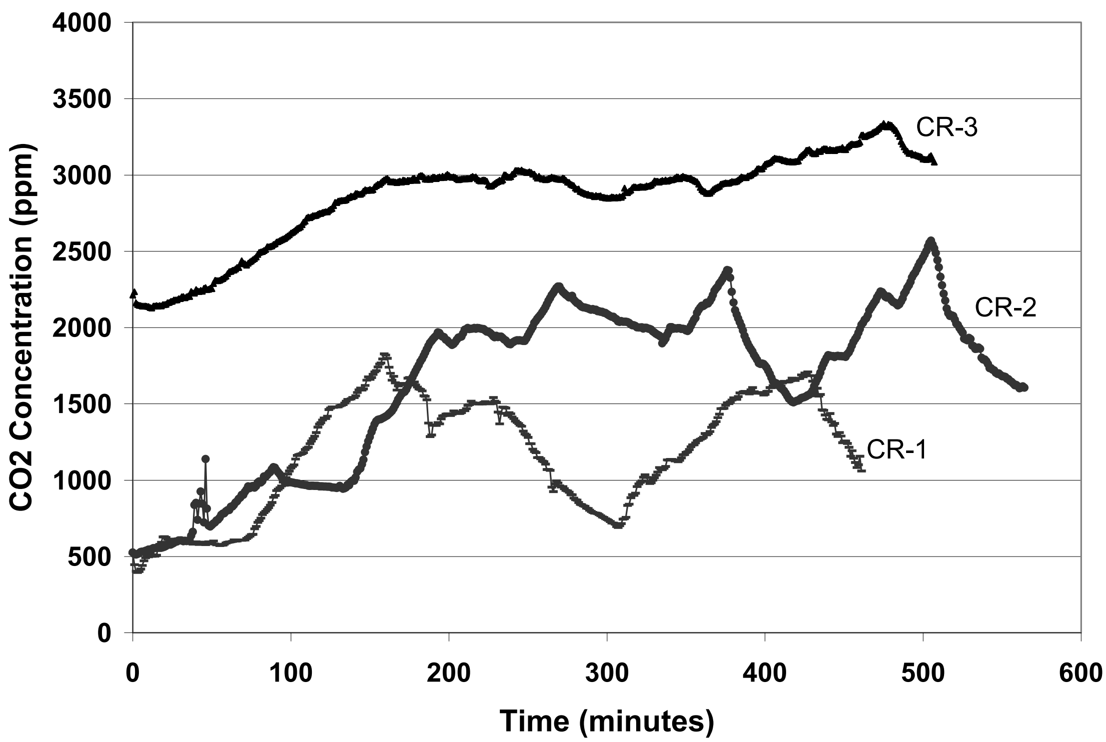

Figure 1. Carbon dioxide profiles as a function of time for three different classrooms.

DISCUSSION

The three CO_2 profiles shown in Figure 1 are illustrative of the dynamic and unique nature of CO_2 profiles in individual classrooms, an observation that has important practical implications. For example, the authors are aware that many consultants in Texas employ short-term, e.g., 10-minute, CO_2 “spot checks” as a means of assessing the adequacy of classroom ventilation. This approach is clearly prone to false conclusions if care is not taken to collect measurements after prolonged student occupation of the classroom. In the case of CR-3 a spot-check measurement anytime after t = 150 minutes would actually provide a reasonable estimate of time-averaged and peak CO_2 concentrations. The same would not necessarily be true for CR-1 and CR-2.

Table 1. Summary statistics for 115 elementary school classrooms in two districts

	All Schools	District B	District G
Time Averaged			
n	115	36	79
Range (ppm)	529-3,112	818-3,112	529-2,899
Mean (ppm)	1,440	1,763	1,292
Median (ppm)	1,286	1,794	1,155
σ (ppm)	642	661	580
Peak			
n	115	36	79
Range (ppm)	744-4,969	998-4,969	744-4,536
Mean (ppm)	2,178	2,657	1,960
Median (ppm)	2,062	2,755	1,854
σ (ppm)	995	1,009	915

n = number of data points; s = standard deviation.

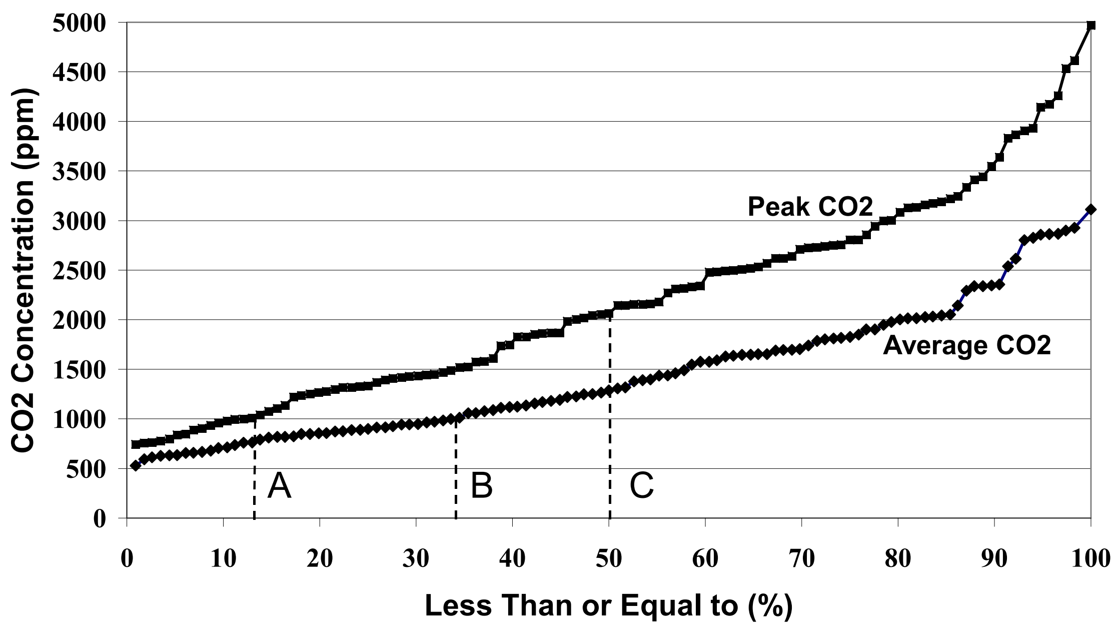

Figure 2. Cumulative distribution plots for time-averaged and peak CO_2 concentrations in classrooms (vertical lines represent % of peak less than 1,000 ppm (A), % of average less than 1,000 ppm (B), and median average and peak CO_2 concentrations (C)).

The dynamic profiles in Figure 1 were largely affected by classroom activities, building design, and design, control, and maintenance of the respective HVAC systems. All three classrooms were served by split system HVAC units that were switched off at night and on weekends. The HVAC systems for CR-1 and CR-2 served only one zone. CR-3 was served by one of four systems that were employed to provide ventilation and comfort for a very large two-story building in which supply air was split between the two floors. The building had no windows. All classrooms on the second floor were designed as an "open environment", divided only by conventional office partitions. There were no exterior doors on the second floor. The ceiling on the second floor was very tall. The outdoor fresh air intake that served the corner of the building where CR-3 was located was purposely blocked.

Classroom CR-1 had an exterior door that remained open during physical education and lunchtime activity periods and following end-of-day departure, hence the rapid decrease in CO_2 concentrations during these periods. CR-2 had an interior door that was also kept open during similar activity periods and was characterized by significant reductions in CO_2 during these periods. Similar responses were not observed for CR-3 during activity periods due to connectivity of classrooms and staggered activity periods between classrooms. The high CO_2 concentrations in CR-3 prior to initial student occupation are a reflection of very poor building ventilation and little decay during the nighttime period. Sampling was completed mid-week. The relatively low increase in CO_2 during the daytime occupation period, despite poor ventilation, was likely due to the large volume (capacity) associated with the second floor of the building.

Sixty-six percent of classrooms were observed to have time-averaged CO_2 concentrations above 1,000 ppm, a percentage that exceeds those reported by Daisey and Angell (1999) and Smedje and Norback (1999). In this study, 20% of classrooms had time-averaged CO_2 concentrations in excess of 2,000 ppm. Peak CO_2 concentrations exceeded 1,000 ppm and 2,000 ppm in 88% and 54% of classrooms, respectively. Peak CO_2 concentrations exceeded 3,000 ppm in 20% classrooms and 4,000 ppm in 5% of classrooms.

The mean time-averaged and the mean peak CO_2 concentrations were both significantly greater in District B than in District G. During walkthrough surveys, we noted that a much higher percentage of outside air intakes that served single zones were blocked in District B classrooms relative to single-zone units in District G. Interestingly, teacher responses to questionnaire issues related to comfort conditions (T, RH, air movement), odors, and classroom environmental quality were not significantly different between the two districts.

Of the 115 classrooms that were monitored, only 8% (10 classrooms) were classified as being within portable buildings. The mean and median time-averaged CO_2 concentrations for the 10 portable classrooms were 1,582 ppm and 1,281 ppm, respectively. The mean and median time-averaged CO_2 concentrations in 105 non-portable (traditional) classrooms were 1,462 ppm and 1,297 ppm, respectively. It was not possible to reject the hypothesis of equality of mean time-averaged CO_2 concentrations between portable and traditional classrooms. A similar result was obtained for mean peak CO_2 concentrations.

Of the 115 classrooms that were studied, 31% had packaged terminal air conditioning (PTAC) units, 25% in District B and 34% in District G. All 36 of the PTAC units were wall-mounted. On average, the equality of both mean time-averaged and peak CO_2 concentrations were rejected when classrooms were separated into those with and without PTAC units, and the alternative one-sided hypothesis of greater mean CO_2 concentrations in rooms with PTAC units was accepted.

Sixty-eight percent of classrooms had entry doors that opened into enclosed hallways that served other classrooms, with nearly identical percentages in District B (69%) and District G

(67%). The equality of mean time-averaged CO_2 concentrations for rooms with and without outside doors could not be rejected. The same was true for peak CO_2 concentrations.

Thirty-six percent of teachers indicated that objectionable odors affect their work in the classroom (35% in District B and 41% in District G). However, 38% of teachers who completed the questionnaire in District G did not answer this question, as opposed to only 5% in District B. We have not been able to determine the reason for the large difference in response rate for this singular question. Interestingly, there was no statistical difference in either mean time-averaged or mean-peak CO_2 concentrations for classrooms in which teachers complained of odor problems, i.e., relative to non-complaint rooms.

CONCLUSIONS AND IMPLICATIONS

The findings presented here represent one component of a much larger study intended to better understand indoor air quality in elementary schools in Texas. The results clearly suggest a cause for concern related to inadequate ventilation of elementary school classrooms. However, the reasons for inadequate ventilation vary considerably from school-to-school and even from classroom-to-classroom. The value of this assessment is two-fold. First, we have quantitatively addressed a problem that was previously suspected based on a sparse dataset. Second, we now have a benchmark that will allow for an assessment of progress if the participating school districts are able to take action to improve classroom ventilation in the future. We are continuing to analyze data to investigate relationships between CO_2, HVAC system design and operation, and staff questionnaire responses. The results presented herein and also obtained through other components of the TESIAS study strongly suggest an immediate need for more research of, and attention to, indoor air quality problems within elementary schools in Texas.

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