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Pandemic experiences with manual ventilation and CO_2 sensing in schools

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Key Messages

- Schools employed a variety of different manual ventilation protocols to increase air exchange in naturally and mechanically ventilated buildings or classrooms during the COVID-19 pandemic. These protocols were generally very effective in increasing air exchange, as indicated by decreases in indoor CO_2 levels.
- In some but not all cases, manual ventilation was associated with thermal or acoustic disturbances; this was dependent at least partly on student preferences.
- Ingress of outdoor pollutants increased in some classrooms, whereas in others manual ventilation decreased pollutants from indoor sources.
- Installing CO_2 sensors in the classroom to encourage occupants to ventilate did not consistently increase ventilation or prevent adverse impacts. However, these benefits are more likely to be realized if CO_2 sensing is coupled with behavioural modification through training or engagement.
- Communication around CO_2 sensing as a means to improve indoor air quality requires a more nuanced understanding of what indoor CO_2 levels do (and do not) entail, and thoughtful integration of CO_2 sensing with other health-protective measures.

Introduction

During the COVID-19 pandemic, epidemiological studies have emphasized the importance of limiting crowds and ensuring adequate ventilation for room occupants, alongside other critical measures, such as masking and distancing. However, one major challenge revealed during the pandemic is that many public and private spaces are not adequately ventilated, and occupants may not be aware of the problem or may not have the means or capacity to adjust ventilation as needed.

CO_2 sensing has been widely advocated as a way to address this knowledge gap and empower building occupants to action and improve indoor air quality (IAQ). Visual feedback from CO_2 sensors offers an opportunity not only to learn about the indoor environment (i.e., whether ventilation in the space is adequate), but to trigger corrective action. As occupants linger in enclosed spaces, their expired CO_2 will gradually accumulate if the air within the space is not exchanged with fresher outdoor air. Immediate corrective actions may include increasing the mechanical ventilation rate, reducing occupancy, or simply opening windows and doors (manual ventilation).

For many people, manual ventilation became a key risk reduction measure for COVID-19 and was widely promulgated by public health organizations.[1] In schools, manual ventilation was a cornerstone of return-to-class strategies, in combination with other measures such as health screening, masking, distancing, physical barriers, cohorting, and air cleaners, among others.[2] The emphasis on manual ventilation was unsurprising, given that public schools are historically under-resourced environments, and in many places are still reliant on natural ventilation. A previous literature review of almost 1,300 schools and daycares globally revealed that many facilities, even those with mechanical systems, were operating without sufficient ventilation.[3] As a precaution, many governments and public health authorities developed manual ventilation protocols in which teachers or students were expected to open windows and doors to manage indoor air quality (IAQ).

In some of these schools, low-cost CO_2 sensors were installed in addition to instituting manual ventilation protocols. The rationale for adding CO_2 sensors is two-fold. First, visual feedback (either as data or a flashing light) can reinforce good ventilation behaviour by teachers and students. Secondly, using a sensor can help to more precisely regulate manual ventilation such that windows are not opened more than necessary, which could compromise thermal comfort or energy efficiency.

The purpose of this review is to help public health professionals, educators, and school administrators understand whether manual ventilation protocols are effective as an emergency measure in schools, especially over the cold winter months, and whether CO_2 sensors further improved ventilation behaviour. The unintended creation of other environmental pollutants or stressors, as a result of the manual ventilation protocols, is also considered. This information will be useful to decision makers seeking to develop an appropriate manual ventilation protocol for schools, either as a pandemic response or as an interim strategy until ventilation retrofits can be completed.

Methodology

The scholarly literature was searched for studies specifically examining the effectiveness of emergency or manual ventilation (e.g., opening doors and/or windows) with or without CO_2 sensors in schools. The search used the EBSCOhost databases, including Medline, CINAHL, Academic Search Complete, ERIC, etc.; key words used are presented in Appendix A. Relevant English-language results were collected from January 2020 to June 2022. Additional references were added via forward and backward chaining of those search results and supplemental searches, as necessary. A full list of results is available upon request.

Studies were selected for review if they evaluated COVID-19-related emergency measures to enhance air exchange through mechanical or natural ventilation systems in school buildings. Modelling studies were excluded. Both peer-reviewed and pre-print sources were considered. Papers were excluded if they reported on CO_2 monitoring in classrooms but did not specifically report on interventions to improve ventilation. After selection, this review included 19 peer-reviewed studies. Each study was assessed by a single reviewer and the results were synthesized narratively. The synthesis was subjected to internal and external review.

Results

This review identified 19 studies in which manual ventilation (opening doors and windows) was used to increase ventilation and decrease the risk of transmission in classrooms, typically in conjunction with other public health measures, such as health screening, the use of masks, and decreased occupancy. Although these emergency ventilation protocols were enacted to reduce transmission risk, none of the studies identified impacts on transmission rates or case counts in the school community. However, it should be noted that ventilation is just one of the numerous environment-, host-, and pathogen-related factors that influence disease transmission. The studies reviewed here were not designed to account for such a high level of complexity, and indeed this would be extremely challenging.

In all studies, CO_2 sensing data were used to estimate ventilation rates and compare the effectiveness of interventions to reduce indoor CO_2 levels, even if CO_2 data were not visible to room occupants. These monitoring data were used to understand whether emergency protocols successfully increased fresh air exchange, which is assumed to decrease transmission risk. **Table 1** provides a summary of the studies covered in this review.

How was manual ventilation carried out?

The majority of schools covered in this review were naturally ventilated, meaning that they did not have a mechanical ventilation, but were instead reliant on the passive flow of air through the building's envelope for air exchange, as well as occupants' personal habits in terms of window opening. However, previous studies looking at naturally, mechanically, and hybrid ventilated schools around the world found that, despite overall lower CO_2 levels and better comfort conditions, the majority of classrooms with mechanical ventilation were still under-ventilated.[3,4] Thus, the findings of this review will likely also be of use in mechanically ventilated schools.

In this context, "manual ventilation" refers to the additional window/door opening protocols or instructions that were enacted to improve upon pre-pandemic ventilation systems (or lack thereof). Manual ventilation protocols fell into five categories. These included:

- Continuous ventilation: All windows and/or doors open all the time;
- Partial continuous ventilation: All or some windows or doors partially open all the time;
- Scheduled ventilation: Windows and doors opened during breaks when the room is not in use (e.g., before class, during recess and lunch breaks, and after class), but closed when the room is occupied;
- Periodic ventilation: Windows and doors opened for a few minutes in a cycle (e.g., open for 5 minutes in every 25–30-minute period);
- Sensor-based ventilation: Opening and closing windows and doors as needed based on visual feedback from a CO_2 sensor.

How effective was manual ventilation as an emergency IAQ protocol?

The effectiveness of manual ventilation protocols was evaluated based on an increase in air changes per hour (ACH), as indicated by decreased indoor CO_2 levels. Manual ventilation was found to be generally quite effective in both naturally or mechanically ventilated schools (**Table 1**), as the vast majority of classrooms across all studies were able to meet or exceed their ventilation target (expressed as ACH or a CO_2 threshold). Generally, classroom CO_2 levels were shown to rise quickly in the morning, peaking in the late morning.[5,6]

However, it is somewhat difficult to compare ventilation effectiveness among these studies due to a number of limitations or special considerations. First, indoor CO_2 levels are dependent on numerous factors, including occupancy, age of occupants, activity level, building construction (number of doors and windows, air tightness, orientation in the landscape, number of floors), presence of mechanical ventilation, the outdoor temperature and season, and whether the room has natural cross-ventilation. Measures that are effective in one setting may not be in another.

Second, there was also great variation in the amount of detail used to describe the interventions and the metrics and thresholds used to describe success. For example, window opening was generally presented as square meters of open window rather than as a proportion of the total surface area of the classroom, which would have been more useful to compare among classrooms. There was also great variation in the target CO_2 level, meaning that "success" in one building would not have been considered effective in another. The challenges around selecting CO_2 thresholds are discussed in later sections.

Finally, the majority of studies were conducted in Spain and Italy where winter temperatures rarely fall below 0°C; only four studies were conducted in more temperate climates. Although natural ventilation was still effective in colder climates, the rate of cooling is expected to be more rapid and finer control of ventilation behaviour is necessary to prevent over-cooling.[6] CO_2 sensors may be useful in this regard by balancing optimized ventilation with maintenance of thermal comfort.

Table 1. Synthesized findings of studies included in the literature review.

Study	Location	Season	Ventilation protocols	Target Value	Occupant Density (m^2/person)	Results
Aguilar et al.[7]	Granada, Spain	January and August 2021	Continuous and partial continuous	6 ACH	8.3	100% (3/3) of trials with continuous ventilation met the guideline vs. 0% with partial continuous
Alonso et al.[8]	Seville, Spain	December to January 2021	Continuous	1000 ppm CO_2	3.85 to 4.05	100% of trials (2/2) met the guideline
Avella et al.[9]	South Tyrol, Italy	December 2020 to May 2021	Non-specified manual protocol vs. sensor-driven	1250 ppm CO_2	2.3	100% of trials for both protocols met the guideline (2 trials per protocol)
Chillon et al.[10]	Vitorio-Gasteiz, Spain	November 2020,	Continuous, partial continuous, no ventilation (control)	1000 ppm CO_2	6.1	Met the guideline for continuous and partial continuous, but not for no ventilation control (4/4 trials)
de la Hoz-Torres et al. [11]	Guimarães, Portugal and Granada, Spain	September to November 2021	Continuous and partial continuous	6 ACH	3.3	100% (4/4) with continuous and 50% with partial continuous (4/8)
de la Hoz-Torres et al.[12]	Guimarães, Portugal and Granada, Spain	September to November 2021	Continuous	900 ppm CO_2	1.1 to 1.8	After implementation, classroom averages were well below target level (742 ppm CO_2 in 8 Portuguese classrooms and 519 ppm in 7 Spanish classrooms)

Study	Location	Season	Ventilation protocols	Target Value	Occupant Density (m^2/person)	Results
Di Gilio et al.[13]	Apulia Region, Italy	January to February 2021	Sensor-driven	1000 ppm CO_2	3.6	91% (10/11) of classrooms met the guideline
Gil-Baez et al.[6]	Anadalusia, Spain	January and June 2020	Scheduled	1500 ppm CO_2	1.7–2	100% (18/18) classrooms were below guideline on average about 57% of instructional time
Konstantinou et al.[5]	Cyprus	May–July 2021	Not described in detail	800-1350 ppm CO_2	2.8	98% of data points gathered from 82 classrooms were below 800 ppm.
Kulo et al.[14]	Sarajevo	October 2020 – February 2021	Scheduled during 3rd period, 2nd and 3rd periods, all three periods, or not at all.	1000 ppm CO_2	Not given	On average, all four classrooms remained below 1000 ppm in October through January, but not February. Worst conditions in poorest ventilated schools.
Lovec et al.[15]	Slovenia	Winters of 2019–2020 and 2020–2021	Scheduled and mechanical	1667 ppm CO_2	3.8	100% (12/12) of classrooms met the guideline, also partly due to large decrease in occupancy
Meiss et al.[16] ,	Valladolid, Spain	September 2020	Continuous, sensor-driven, schedule and periodic	900 ppm CO_2	2.8	CO_2 above guideline 0.3% of time for continuous ventilation, 1.9% of time for sensor-driven ventilation, 7.1% of time for scheduled ventilation, 6.23% of time for periodic ventilation.
Miranda et al.[17]	Southwest Spain	January 11–19, 2021	Continuous, partial continuous, and sensor-driven	950 ppm CO_2	10.3	Average CO_2 levels of 530 ppm CO_2 for continuous ventilation (n=15), 608

Study	Location	Season	Ventilation protocols	Target Value	Occupant Density (m^2/person)	Results
						ppm for partial continuous (n=2) and 606 for sensor-driven (n = 1).
Monge-Bario et al.[18]	Pamplona, Spain	March 2020 and January 2021	Scheduled ventilation vs. no protocol	1000 ppm CO_2	<3	Average of all classrooms was 2478 ppm CO_2 pre pandemic and 1105 in Jan 2021, based on 9 classrooms.
Mori et al.[19]	Sapporo, Japan	June–January 2021	Continuous, shifting to scheduled during coldest months	1500 ppm CO_2	Not given	Only 2 classrooms monitored closely; met guideline 60% and 80% of the time.
Muelas et al.[20]	Zaragoza, Spain	December 2020	Continuous, partial continuous, scheduled, periodic, periodic/partial continuous	700–800 ppm CO_2	3.2	Continuous most effective (mean, ~500–650 ppm); the remaining interventions led to higher peak CO_2 levels (900–1200 ppm)
Vassella et al.[21] .	Switzerland	Winter	Sensor-driven with supporting educational and communication tools	2000 ppm CO_2	Not given	Median CO_2 level dropped from 1600 to 1097 ppm after the intervention, based on 23 classrooms.
Villanueva et al.[22]	Ciudad Real, Spain	October 2020	Continuous	700 ppm CO_2	2.5	74% (14/19) classrooms met the guideline
Zhang et al.[23]	Netherlands	April and May 2021	Scheduled vs. mechanical ventilation	NA	6 and 11 m^2/person, respectively	On average, 869 ppm CO_2 for scheduled (n=2) and 832 ppm for mechanical (n=5). Note very low occupancy.

What factors increased ventilation effectiveness?

Open window surface area. Unsurprisingly, having more window surface area open at the same time led to greater overall ventilation rates.[5-7,11,23] For example, Gil Baez et al.[6] deemed natural ventilation to be effective in nine primary and secondary schools in a Mediterranean climate when the open window area was ~10% of the total surface area of the classroom, although the target CO_2 level used was quite high (1500 ppm).

In addition, Muelas et al.[20] found that distributing the total open window area across several windows was far more effective than opening a single window by the same amount. This approach resulted in a lower indoor CO_2 concentration and was less likely to create CO_2 gradients, an indicator of poor mixing.

Cross ventilation. The ability to cross-ventilate a classroom (i.e., the rooms had windows and/or doors on opposite sides of the classroom) made a large difference in air exchange compared to non-cross-ventilated rooms.[8,16] Cross ventilation prevents the formation of gradients, in which students farthest away from the window are less or much less likely to receive fresh air.[20,23] In some cases, cross ventilation was necessary to achieve the desired ventilation rate.[20] Some studies examined classrooms that cross-ventilated to an interior corridor rather than to the outside. Cross ventilation to a corridor was less likely to achieve target ACH[11]; however, cross-ventilation through an open door to the corridor was still better than keeping the door closed.[20]

Occupant density. Higher occupant density was associated with greater CO_2 levels and greater need for ventilation.[6] Amongst the classrooms in this review that met their guidelines, occupant density ranged from 1 m^2 per person to more than 10 m^2 per person. In some studies comparing pre-pandemic and pandemic ventilation rates, the large decrease in occupant density is a major contributor to decreased CO_2 levels observed (e.g., Lovec et al.[15]).

Age or activity of occupants. Two studies found that upper-level classes had higher CO_2 levels than primary or preschool classes,[6,22] most likely due to age-related differences in CO_2 generation and because upper-level classes had higher occupancy and longer hours. Within the same age group, activity in the classroom also affected the rate of CO_2 accumulation. Muelas et al.[20] demonstrated clear differences between activity types (free movement, a mostly seated lesson, and an exam with little movement or speech) in the same classroom on the same day.

Building type. Lovec et al.[15] compared buildings with natural ventilation built in the 1950s, 60s, and 70s, all with the same south/southeast orientation, as well as a 1980s building with mechanical ventilation. During the pandemic, all naturally and mechanically ventilated public buildings in Slovenia were required to have open windows to air out the space at least 15 min before occupancy, and after. It is difficult to draw conclusions as to the effect of building age due to the small sample size. Overall, CO_2 concentrations decreased by ~30% for all classrooms compared to pre-pandemic levels due to both the manual ventilation protocol as well as decreased occupant density (from 2.5 to 2.9 m^2 per person).

Existing ventilation systems. Lovec et al.[15] found that although mechanically ventilated buildings were well below the guideline value of 1667 ppm CO_2 pre-pandemic, additional airing and decreased occupancy served to further decrease CO_2 levels to approximately 600 ppm. Likewise, Zhang et al.[23] showed that although the manual ventilation protocol did not perform as well or as reliably as mechanical ventilation or hybrid systems, it was still an overall improvement and able to maintain the room below 800 ppm CO_2.

Aspect or orientation. The position of the building on the landscape and exposure to prevailing winds and sunlight (or shielding from these) can affect how air flows through, up, and out of a building. For example, de la Hoz-Torres et al.[11] found that identical classrooms on opposite sides of the building using the same manual ventilation strategy had very large differences in ventilation rates due to differences in external air flow conditions. Similarly, vertical position within in the building (being located on the first vs. second floor) can generate differences in air flow (due to buoyancy or the stack effect) that will affect the ventilation rate.

Effect of the manual ventilation protocol. Several studies attempted to compare manual ventilation protocols; the advantages and disadvantages of the various protocols are compared in **Table 2.** Muelas et al.[20] placed 17 CO_2 sensors in a single classroom and monitored the room under different protocols, which were repeated at different times of the day over 4 days. These results showed that, overall, continuous and partial continuous ventilation (always having some windows fully or partially open) functioned better than scheduled (during breaks) or periodic ventilation (opening on a 5–15 min cycle). The latter strategies were characterized by a sawtooth pattern of rapid CO_2 accumulation and rapid decline, with peaks above the desired threshold.

Similarly, Vassella et al.[21] also observed a sawtooth pattern when using scheduled ventilation, with peaks near 2000 ppm CO_2. Periodic ventilation resulted in a lower overall CO_2 concentration, comparable to partial continuous ventilation, although the peak concentrations still approached 900 ppm. This is consistent with previous modelling work showing that periodic ventilation on a 5–20 min schedule did not create enough air flow to achieve the desired ACH.[24]

Meiss et al.[16] compared continuous ventilation with ventilation that was either scheduled around class breaks or periodically executed for 5 min ever 25 min with coordinated window/door opening with the classroom across the hall. All protocols (alongside decreased occupancy) decreased the time that CO_2 levels were above the threshold (1000 ppm) from more than 90% to less than 10%. Continuous ventilation appeared to produce the lowest overall CO_2 levels; however, the differences between treatments were marginal and the sample size was small. Teachers who were asked to coordinate window opening with the class across the hall (to promote cross ventilation) reported that the intervention was onerous and not feasible in the long run.

Miranda et al.[17] examined 18 university exam sessions conducted under continuous ventilation (15 sessions), partial continuous ventilation (two sessions), and sensor-driven ventilation (one session). All interventions successfully maintained room CO_2 well below their chosen threshold of 800 ppm, with marginal differences (<100 ppm) between them.

Table 2. Synthesized findings regarding the advantages and disadvantages of manual ventilation protocols.

Ventilation Protocol	Advantages	Disadvantages
Continuous ventilation *All windows and doors open throughout the day*	Easy to use. Protects people in the same room at same time. Consistently achieves the lowest CO_2/highest ACH.	Very high ACH may exacerbate cold/noise issues.
Partial continuous ventilation *Windows and/or doors partially open through the day*	Easy to use. Protects people in the same room at same time. May not be as cold/noisy as fully opening windows and doors.	Occasionally not sufficient to substantially increase air exchange; must be assessed on a case-by-case basis.
Scheduled ventilation *Ventilation before school, during breaks, and after school*	Simple and easy to remember; noise/cold have less impact because the room is empty during airing.	Does not protect occupants of the same room at the same time. Does not let indoor generated pollutants disperse.
Periodic ventilation *Opening windows for a few minutes every 25–30 minutes*	Protects people in the same room at the same time without allowing too much cold/noise. Allows indoor generated pollutants to disperse.	May be perceived to be more onerous.
Sensor-driven ventilation *Opening windows when triggered by visual feedback from a CO_2 sensor*	With engaged users, may help users to control CO_2 around a set point, not so low as to cause cold/noise issues, without exceeding the target level. Has pedagogical value for students.	Needs an engaged user; not necessarily better than other methods without an engaged user; responding to the monitor may disrupt flow of classroom activities.

Did manual ventilation or CO_2 sensing create other undesired impacts?

The key concerns around manual ventilation, or natural ventilation more generally, are that indoor conditions can become too hot, too cold, too noisy, or otherwise impacted by the infiltration of particulate matter (PM), ozone (O_3), total volatile organic compounds (TVOCs), or other pollutants from the outdoor or indoor environment. Schools can also be impacted by increased energy costs related to increased heating or cooling demand when windows or doors are opened.

Thermal comfort. The majority of studies reported on indoor temperatures during manual ventilation. In some cases, this revealed temperatures outside of the desired range for substantial portions of the day.[5,7-10] However, only a handful of the studies evaluated thermal comfort, either directly via surveys[12,18,19] or estimated through modelling approaches.[17] For example, Miranda et al.[17] studied 18 university exam sessions conducted under three different ventilation conditions during a cold winter (mean outdoor temperature, 10.8°C; range, 0–18°C). Surprisingly, as long as outdoor temperatures were above 6°C, indoor thermal conditions were generally found to be acceptable. At temperatures greater than 12°C, classes could have windows wide open with no thermal consequences. This approach demonstrates how it may be necessary to adapt manual ventilation protocols for a given climate or season. Monge-Barrio et al.[18] examined thermal comfort across a fairly narrow range and found that more students reported being comfortable when the temperature was between 19°C and 20°C, and students in poor health reported feeling tired at temperatures >20°C. However, the average classroom temperature of 18°C did not appear to affect learning and students were more likely to report being comfortable later in the day. It is important to note also that different groups of students may present drastically different thermal preferences.[12]

Acoustic conditions. Several studies examined noise disturbances, which depended on factors such as the building's orientation on the landscape, the presence of greenspace around the building, and the presence of nearby noise generation, such as busy roadways. Aguilar et al.[7] found that only the maximum number of windows open produced sufficient air exchange, but because windows opened onto a busy street, noise levels increased in both summer and winter. Peak noise levels were in the range of 60–70 dBa, which is well above the typical guideline value of 35 dBa. Similarly, comparison studies in a Portuguese and a Spanish university found that manual ventilation not only increased noise levels,[11] but led to acoustic disruption that may have affected learning performance.[12]

Exacerbation of pre-pandemic issues. In some cases, moving to an emergency manual ventilation protocol only exacerbated pre-pandemic issues with thermal or acoustic comfort. Alonso et al.[8] found that moving from natural ventilation with random window opening to continuously opened windows shifted the proportion of "uncomfortable" instructional hours from 50% to greater than 80%. Similarly, the classrooms examined by de la Hoz Torres et al. [11] had existing noise problems. All classrooms studies were at or above the recommended limit of 35 dBA for ambient noise; opening windows for ventilation made this worse. The authors noted that physical distancing may have also contributed to noise issues, as children seated at the back would have an even lower signal to noise ratio when straining to hear the teacher's voice over the ambient noise.

Ingress/egress of air pollutants. Several studies also considered changes in exposure to other pollutants, including PM and TVOCs. Chillon et al.[10] observed that opening windows increased indoor $PM_{2.5}$ levels, trending toward observed outdoor levels, and Villanueva et al.[22] noted that outdoor play in a sandbox appeared to increase indoor PM in the classroom after the break. However, the majority of studies detected peak PM levels when windows were closed and the room was highly occupied, suggesting that indoor PM generation was more impactful than outdoor sources.[5,6,14,19] Similarly, Meiss et al.[16] found that manual ventilation reduced indoor TVOCs from 29% time out of range to just 10%. However, none of the studies examined here were designed to identify the source of pollutants or factors contributing to their levels. Previous work in the US has shown the various indoor and outdoor sources most likely to contribute to classroom PM, TVOCs, and other pollutants.[25]

Energy efficiency. Several studies noted that sacrificing energy efficiency was necessary to meet thermal comfort goals.[8,18,19] In fact, Monge-Barrio et al.[18] found that some schools incurred 30–40% increases in heating oil usage to compensate for thermal discomfort during manual ventilation, whereas other schools saw large decreases in heating costs due to cancellation of extracurricular activities. In Northern Japan, Mori et al.[19] noted increased energy consumption until outdoor temperatures dropped to 0°C, at which point windows were closed and further losses were not incurred. Overall, increased manual ventilation at temperatures above freezing resulted in a 7% decrease in energy efficiency during the heating season.

Did CO_2 sensing improve ventilation effectiveness or reduce adverse impacts?

Although the importance and utility of CO_2 sensing to regulate classroom IAQ was a key assumption in all of the studies reviewed, the literature reviewed did not adequately demonstrate the additional value of CO_2 sensing over and above the implementation of the ventilation protocol itself. There are two reasons for this. The first is that the majority of the studies using sensor-driven ventilation compared results on different days, in different classrooms, or with other design flaws that made it difficult to know whether any improvement in ventilation effectiveness was due specifically to the sensor.

Second, with the exception of one study,[21] the literature did not place enough emphasis on behavioural change when implementing CO_2 sensing. Several studies noted poor compliance with sensor-driven ventilation, whereas in others a particularly diligent teacher was the difference between success and failure.[9,13,16,19] Simply installing CO_2 sensors (or mandating ventilation) in a classroom and expecting improved air exchange ignores the critical factor of human behaviour.

Di Gilio et al.[13] monitored indoor CO_2 levels in nine classrooms before and after instituting a manual ventilation protocol supported by CO_2 sensors. Although the intervention was very successful in reducing and maintaining CO_2 levels below the target level (1000 ppm) in all but one classroom (which was the result of noncompliance), it was not clear how much of this success was due to CO_2 visual feedback as there was no treatment group with the manual ventilation protocol but without sensors.

Meiss et al.[16] examined five different manual ventilation strategies in a Spanish primary school in February 2021, two of which included the use of a CO_2 sensor. Teachers were instructed to follow a specific protocol (either scheduled ventilation during class breaks, or continuous ventilation), but then also use the CO_2 sensor to avoid exceedances. Although it is difficult to draw conclusions due to the small sample size (two classrooms per treatment), the two treatments with the lowest overall CO_2 levels and least time out of range (threshold of 1000 ppm CO_2) both employed a CO_2 sensor and either scheduled or continuous ventilation. In addition, although manually ventilated classrooms were all colder than desired, the presence of CO_2 sensor appeared to reduce the amount of time that the temperature was outside of the desired range (21–23°C). Classrooms that employed scheduled ventilation but no sensor were too cold 65.8% of the time, compared to only 41.8% of the time with scheduled ventilation and CO_2 feedback, and 18.7% of the time with continuous ventilation and CO_2 feedback. However, the best overall strategy for maintaining adequate temperatures was partial continuous ventilation without a CO_2 sensor (too cold only 11% of the time), which entailed CO_2 exceedances only 6% of the time.

In contrast, Miranda et al.[17] found that having access to CO_2 sensor data did not result in a substantial difference in CO_2 concentrations, nor did it allow the occupants to substantially reduce thermal discomfort compared to other classrooms using continuous or partial continuous ventilation without CO_2 visual feedback.

Avella et al.[9] examined paired classrooms (using manual ventilation with or without CO_2 visual alerting) in four schools in Italy. In the first school, CO_2 visual feedback appeared to elicit an overall increase in window opening and decrease in CO_2 levels compared to the classroom without a sensor, and thermal discomfort was largely avoided. The teachers and students were reported to have engaged positively with the sensor and diligently obeyed the high CO_2 warning. However, CO_2 visual feedback did not have a consistently positive effect on average CO_2 values or CO_2 exceedances (values >1200 ppm) in the remaining three pairs of classrooms. In two of the schools, pandemic-related reduction in occupancy (to ≤50% of previous) meant that CO_2 levels remained well below the acceptable threshold regardless of sensor use. In terms of user engagement, teachers indicated lack of compliance due to concerns with cold outdoor temperatures. In the kindergarten classroom, responding to the sensor was a distraction from the requirements of teaching very young students. One teacher was particularly diligent in opening windows as a personal habit, resulting in very low CO_2 levels even though no sensor was present. In addition, CO_2 values did not always show a consistent relationship with the amount of time windows were left open. This inconsistency emphasizes the extreme difficulty of controlling for the many confounding factors that can affect air flow in a space. Overall, Avella et al.[9] did not demonstrate that CO_2 visual alerting leant an additional benefit in terms of ventilation effectiveness or behaviour of the occupants.

In northern Japan, students and teachers showed relatively high compliance with sensors alerts and an overall positive attitude toward the CO_2 sensor. However, as colder months approached and as temperatures approached freezing, the number of windows open decreased and the number of students reporting being slightly or very cold increased to approximately 40%.[19] The authors noted that one teacher was able to successfully control CO_2 levels to below 1000 ppm using continuous partial ventilation with a single larger airing once in a while.

Only one study in this review coupled CO_2 sensing with a behavioural intervention. Vassella et al.[21] developed educational aids (flyers, a detailed lesson plan, and teacher instructions) to increase awareness among and enlist participation of students and teachers over the course of several weeks before the intervention. The intervention also included an app that helped users calculate the length of the ventilation interval to be carried out over the break, and generated metrics to help users understand how the day went. Importantly, however, users were not responding to the CO_2 sensor by opening more windows; windows were opened only during break and the purpose of the app was to determine the duration of that opening. Not having to respond to sensor alerts may have reduced disruption to activities. The intervention reduced the median CO_2 levels from 1600 ppm to 1097 ppm, although the CO_2 threshold was quite high (2000 ppm). Furthermore, these large reductions were observed both in classrooms that had previously shown good compliance with the ventilation protocol, as well as in classrooms that had not. This signals that the behavioural intervention (training and engagement) was successful. Finally, the benefit of this approach over others is that there was no difference in thermal profile compared to the control.

Considerations for developing a manual ventilation protocol

The studies reviewed demonstrate that emergency manual ventilation is typically quite effective for reducing indoor CO_2 concentrations (sometimes far more than required). However, the results can be variable and excessive ventilation may create discomfort and other issues. Therefore, it is necessary to evaluate individual classrooms (or groups of similar classrooms) to determine what protocol will be sufficient for a given season. As noted by Meiss et al.,[16] schools may benefit from having a manual ventilation protocol for normal use, as well as a more stringent protocol for emergencies such as a respiratory outbreak. This section provides considerations for developing manual ventilation protocols; however, any physical changes to classrooms should be reviewed by professionals with the appropriate expertise to understand how those changes may affect air flow in the classroom and the building.

Selection of a CO_2 threshold

Selecting an appropriate CO_2 threshold can be complicated due to the way in which occupants may confuse or conflate different IAQ risks. To create this more nuanced understanding of CO_2 levels, occupants should understand that CO_2 sensors provide **limited** insight into three different kinds of indoor air risk:

- Risk of exposure to CO_2 itself. Exposure to indoor CO_2 may affect feelings of fatigue, cognitive performance, respiratory health, and absenteeism.[3,26,27] However, these effects are short-term and reversible with removal to fresh air. Surpassing the CO_2 target level does not represent an imminent health threat.
- Risk of exposure to other pollutants. High CO_2 levels/poor ventilation may mean that other harmful pollutants are able to accumulate within the space. However, these pollutants may not accumulate at the same rate as CO_2 or may not be related to occupancy (e.g., off-gassing from building materials or radon from underlying soil). As such, they may still be present at hazardous levels even if CO_2 is low.[28,29] Thus, setting even a low CO_2 threshold may not protect occupants from other indoor pollutants.

- **Risk of infectious disease.** Occupying an under-ventilated environment may increase the risk of transmission of respiratory disease. However, as with other pollutants, the concentration of virus on the room may not be directly related to the number of people in the room or may be reduced by other health protective measures. Thus, increasing air exchange may not be sufficient to eliminate the risk of disease.

These limitations of CO_2 as an IAQ metric create some challenges when selecting an appropriate target level. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) does not currently promote a single indoor CO_2 level.[29] Although the concentration of 1000 ppm CO_2 is frequently attributed to ASHRAE, this is related to an earlier standard (ASHRAE 62 in 1989), in which CO_2 was used as a proxy for the perception of body odour. Health Canada has established a residential indoor CO_2 guideline of 1000 ppm based on literature regarding the effects of CO_2 exposure on effects such as fatigue and cognitive performance.[27] However, although health-based, this level has no relevance to preventing the spread of respiratory disease. Some authors have used CO_2 levels to calculate the "rebreathed" fraction of air in a given space, and then linked that fraction to the risk of infection and used the relationship to recommend CO_2 thresholds for indoor spaces based on activity level, vocalization, and use of masks.[30] However, as mentioned above, these studies do not account for the various ways virus levels may change or the difference in risk posed by different pathogens, both of which may change independently of CO_2 emission from occupants.[29,31,32] Due to these factors, and others, it is difficult to establish a clear quantitative relationship between different types or rates of ventilation and the prevention of respiratory disease.[33,34]

Given that there is **no CO_2 threshold that eliminates respiratory infection risk**, and considering the challenges of ventilating spaces without impacting comfort, a practical approach is required. That is, occupants should seek to keep CO_2 levels as low as possible without causing disruption or discomfort. Any target level selected should be based on evaluating what is possible for a given space. The target level, therefore, **should not be understood as a "red line" or a margin of safety**, but as a reminder to ventilate. Ventilation is just one of the health protective measures necessary to limit the spread of respiratory disease.

CO_2 sensors can also be used to confirm that the spaces in use conform to the applicable codes and standards through the use of a CO_2 calculator. For example, if the regulator demands that classrooms be ventilated at a given rate (commonly around 5-6 ACH, or 10 ACH during a respiratory outbreak, as per ASHRAE[35]), a convenient online calculator[36] can help to determine whether the CO_2 concentration in a room corresponds to that rate, while also considering the classroom's dimensions, number of occupants, and their activity level. Again, as with a CO_2 threshold, there is no specific ACH that will eliminate infection risk. However, it does allow occupants, administrators and regulators to have a more informed dialogue regarding whether the classroom is meeting expectations in terms of ventilation.

Selecting a CO_2 sensor

Cost is likely to figure prominently in selecting a CO_2 sensor, particularly when many sensors will be needed. However, the rapidly growing low-cost sensor market means that buyers must beware when selecting a device.[37,38] Decision makers should consider the following:[39]

- What claims are made regarding sensor accuracy, detection range, and detection limits?
- Does the school want additional functionality (e.g., being able to also track other IAQ parameters such as PM or VOCs)?
- What is the battery lifespan and what is required to recharge or replace batteries?
- What is the sensor's lifespan, is it durable, and is it covered by a manufacturer's warranty and/or customer support?
- Can the sensor be calibrated and how often is this required? Does the manufacturer provide adequate instruction on how to do this?
- What data storage and analysis capabilities does the sensor require? How easy is it to review, analyze, and share data?

Additional resources for selecting, installing, interpreting and maintaining air sensors can be found at the US Environmental Protection Agency's *Air Sensor Toolkit*,[40] as well as the EPA's *Air Sensor Guidebook*.[39] These resources are not specific to CO_2 sensing and may be useful to schools wishing to monitor for other indoor air pollutants.

Evaluating the space

Zhang et al.[23] and Muelas et al.[20] provide an overview of how to evaluate a classroom for CO_2 levels and CO_2 gradients (an indicator of poor air mixing) using multiple sensors. Although it may not be possible to use numerous sensors, Zhang et al.[23] recommend using at minimum two sensors for naturally ventilated classrooms and classrooms with mechanical exhaust (window fans), and one sensor for mechanically ventilated classrooms, which tend to have better mixing. One of these sensors should be placed in a well-mixed region of the room, while the other should be placed farthest from the fresh air supply (the open door or window). This will help to ensure that even the "least favourable" spot in the room is being considered. Please refer to Zhang et al.[23] for more detailed description and diagrams.

Although a sampling height of 1.5 m is often recommended, Muelas et al.[20] found that sensors placed at this height tended to overestimate the room average, whereas samplers at 0.75 m substantially underrepresented the value. Sensors placed at 2.2 m above the students, which avoids both breath plumes and collisions with students, provided a more reliable estimate of room average CO_2.[20] The study also found that placing sensors on the walls tended to underestimate CO_2 levels, due to poor mixing at the edges of the room.

Finally, it is important to document environmental conditions (indoor/outdoor temperature and outdoor CO_2) and occupancy (number of occupants, age groups, and activity level). A ventilation protocol developed under one set of conditions may not be functional under another. For example, 20 children in a classroom in January may require a different protocol than the same room in summer, with 15 adults having choir practice.

By monitoring CO_2 in one or more positions in an occupied classroom under the worst conditions (very cold or very warm outdoor temperatures), occupants may judge which of the manual ventilation protocols in **Table 2** meets their criteria. Criteria may include:

- Maintaining an acceptable CO_2 concentration, based on a nuanced understanding of risk.
- Not creating an onerous or unsustainable burden on occupants.
- Avoiding thermal and acoustic discomfort.
- Avoiding the introduction of other hazards.

The standards for assessing thermal comfort are ASHRAE Standard 55-2020[41] and ISO-7730:2005.[42] However, more practicable and less technical surveys for thermal and acoustic comfort can be found in the literature, including in papers reviewed here.[12,18] In essence, "comfort" in these methods is defined as the conditions under which some majority (often 80%) of the occupants are in a neutral or non-disturbed state.

Once CO_2 sensing has been used to identify a functional manual ventilation strategy, it may not be necessary to keep the sensor in place if good ventilation behaviour has been established.[43] The sensor can be used to evaluate or monitor other spaces and/or brought back periodically for checks. Occupants may or may not wish to keep a monitor in the classroom based on personal preference.

Consider other technologies and strategies

Other considerations for devising an emergency ventilation protocol are the use of add-on technologies and the integration of other necessary public health measures. For example, the burden on occupants (or disruption to activities) can be reduced if CO_2 sensors are instead integrated into ventilations systems. An in-classroom example might be CO_2 sensors coupled with automatic window louvers and exhaust fans,[6,24] which has previously shown to be more effective than manual ventilation in terms of both CO_2 and temperature control.[44] Other options such as awnings may be useful to mitigate noise or heat exposure caused by opening windows.

Regarding integration with other public health measures, it should be emphasized that CO_2 sensing and ventilation address (primarily) the longer-term and longer-range risk of respiratory emissions accumulating indoors. Improved ventilation on its own cannot address the risk of respiratory disease transmission, which occurs through multiple modes over short and long distances. For example, the relatively slow exchange of air through ventilation does not address the extremely rapid exchange of particles between two people interacting face to face, as do measures like masking or other barriers.[31] Occupants should also be aware that although air cleaners and masks remove particulates (including aerosol-borne viruses), they do not affect CO_2 emissions or concentrations in the room.

Engaging occupants through training

The literature reviewed here showed mixed results regarding the utility of sensor-driven ventilation. Previous work has emphasized the critical importance of engaging users, through training or IAQ education, and the importance of leaving enough time for this training to occur. Geelen et al.[43] looked at the effect of three interventions on CO_2 levels in 81 Dutch primary schools. The interventions included advice on how to ventilate the classroom manually, ventilation advice supported by a CO_2 sensor, or ventilation advice with ventilation-themed lessons plans. At the end of the six-week study, providing ventilation advice with supporting lessons plans better engaged students and had a longer lasting effect on maintaining low CO_2 levels than the sensor intervention. Examples of lesson plans and training materials can be found through Geelen et al.[43] and Vassella et al.[21]

In addition, occupants should understand that the selected target CO_2 level is not a "safe" level, but simply a risk reduction tool to be used in conjunction with other measures such as masking, hand hygiene, barriers where appropriate (e.g., at school reception),[31] and others.[1]

Surpassing the CO_2 threshold does not mean that adverse health effects will occur. Likewise, staying below the threshold does not eliminate risk.

Begin activities necessary to permanently improve classroom indoor environmental quality (IEQ)

The ventilation protocols described in this document are not intended as a permanent solution for poor ventilation in schools. Ideally, CO_2 sensing in schools will help to identify the worst-affected buildings or areas and trigger remediation, while providing some measure of risk mitigation in the interim.

Creating better and healthier school spaces will require re-evaluating how school buildings are designed, ventilated, and operated,[45] and may lead to necessary compromises in indoor air quality, energy efficiency, and thermal comfort.[46] However, action to improve ventilation and air cleaning in schools is urgently needed, as the increased frequency of climate change-induced wildfire and extreme heat mean that manual ventilation may not be possible. In this way, the pandemic has served as a necessary call to action for improving school IEQ and protecting children's health.

Summary

This evidence review found that although manual ventilation is effective in increasing air exchange overall (as indicated by a decrease in CO_2 levels), increased connectivity to the outdoors did increase issues with cold, noise, and occasionally with pollutants (PM) for schools situated in unfavorable environments. However, in many of the schools examined, manual ventilation did not result in large deviations from the desired temperature range, and slight decreases in indoor temperatures did not result in overt dissatisfaction.

These results highlight the tradeoffs that must be negotiated when schools are dependent on natural ventilation during a respiratory pandemic, and the many factors that will impact the ventilation rate. CO_2 sensors may be useful both for evaluating individual classrooms (or groups of similar classrooms) to find a workable protocol, and to help occupants stay on track when implementing the protocol. Although the studies reviewed here did not reveal a marked benefit of CO_2 visual feedback on either the ventilation rate or avoiding adverse impacts, greater efforts to educate occupants and create better ventilation habits may help to realize this potential. In the long term, retrofitting schools to face current and future IAQ challenges will ensure that poor ventilation in under-resourced schools does not exacerbate respiratory health inequities in students.

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Appendix A

Keywords and terms used in the literature search, based on the PECO framework:

Problem
indoor OR IAQ OR room OR office OR restaurant OR dining OR shop OR business OR premise OR house OR home OR residence OR apartment OR condominium OR condo OR apartment OR flat OR building OR arena OR gym OR classroom OR class OR school OR university OR daycare OR "day care" OR centre OR center OR institution OR hospital OR clinic OR lab OR laboratory OR "confined space"

AND

Exposure
"carbon dioxide" OR CO2

AND

Comparator
Intervention OR ventilation OR ventilate OR ventilated OR HVAC OR "mechanical system" OR "air conditioning" OR heating OR "air conditioning" OR window OR opening OR "air flow" OR exchange OR "air change" OR actions OR airing OR fans OR outbreak
sensor OR instrument OR detector OR detection OR "tracer gas" OR micro-sensor

AND

Outcome

(reading OR analysis OR analyses OR level OR amount OR proportion OR estimate OR measure OR measurement OR impact OR evaluation OR evaluate OR determine OR limitation OR capability)
(reduce OR reduction OR decrease OR mitigate OR mitigating OR mitigation OR prevention OR prevent)
("infectious particle OR bioaerosol OR "particulate matter" OR PM2.5 OR "air quality")

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