EMG-SPI-B: Application of CO_2 monitoring as an approach to managing ventilation to mitigate SARS-CoV-2 transmission

EMG has previously given guidance[1] on the importance of ventilation to mitigate transmission of COVID-19 including recommending appropriate ventilation rates and providing baseline on carbon dioxide (CO_2) concentrations in indoor air that indicate good or poor ventilation. This paper aims to provide an update to the previous paper, and to consider in more detail the evidence for the physical and behavioural factors that would need to be considered to deploy CO_2 sensors as means to identify highly occupied and poorly ventilated spaces or to enable occupants to manage ventilation provision in a space.

Key points

- Ventilation is an important COVID-19 mitigation measure but as air is invisible, individuals and organisations can struggle to manage ventilation effectively
- CO_2 is in exhaled breath and therefore represents the fraction of air that has been exhaled by individuals in the space. It is an effective proxy for occupancy and/or ventilation but it is not a direct proxy for infection risk.
- CO_2 monitoring can be a cost-effective way of helping to identify spaces with high occupancy and/or poor ventilation and for actively managing ventilation in a space. It can be used to enable a good balance between ventilation, thermal comfort, and energy use.
- Introducing CO_2 monitoring is technically straightforward but requires clear guidance that is co-designed with users to enable monitors to be used effectively to sustain better ventilation and occupancy behaviours. CO_2 monitoring is not a direct mitigation; it is a means to guide additional actions to manage ventilation.

Evidence Summary

Effectiveness of Ventilation as a COVID-19 mitigation

- Ventilation can effectively reduce airborne transmission of SARS-CoV-2 beyond 2m but does not reduce transmission via close range aerosols and droplets or via fomites *(high confidence).* Airborne transmission beyond 2m has been indicated as a risk factor for super spreading outbreaks *(medium confidence).*
- Spaces with ventilation that meets current and recent UK building standards are likely to pose a lower risk for airborne transmission *(medium confidence).* Although some variants are more transmissible, there is not currently any epidemiological evidence to suggest that ventilation rates should be increased beyond those previously indicated *(low confidence).*
- Public and business understanding of ventilation as a COVID-19 mitigation is lower than measures such as cleaning and hand hygiene, even though it may be as important to controlling transmission *(medium confidence).*
- The quality of ventilation across UK building stock is unknown. There is evidence to suggest that a wide range of building types are not adequately ventilated, especially in the winter months; this may be due to operation, maintenance, or design *(medium confidence).*
- Business understanding of their ventilation approach and systems is low *(medium confidence).* Many organisations are unaware of their ventilation provision and lack the tools and knowledge to effectively manage it. It may be more of a challenge in organisations which do not have dedicated facilities managers, those without control over their buildings (eg. PFI, rented), and those with fewer resources to invest in assessing and improving ventilation *(medium confidence).*

- There are multiple barriers to individuals being able to manage ventilation including: balancing ventilation with thermal comfort and health requirements, noise, security and energy use; inadequate ventilation provision; lack of agency to make changes in their environments; lack of understanding about how well ventilated an environment is or the actions that can be taken to manage it; challenges to negotiating or agreeing actions with others *(high confidence).* These challenges are more likely in settings and communities with higher levels of deprivation *(medium confidence).*

Use of CO_2 monitoring to manage ventilation and occupancy

- CO_2 monitoring can give an indication of the proportion of air in a room that is exhaled breath and the occupancy and/or effectiveness of ventilation in a setting *(high confidence).* It does not provide a direct measure of infection risk, or a direct measurement of ventilation rates *(high confidence).*
- A consistent CO_2 value < 800ppm (absolute value) is likely to indicate that a space is well ventilated but does not mean that an environment is risk free of COVID-19 risks *(high confidence).*
- Sustained high CO_2 values (>1500ppm) are likely to indicate overcrowding or poor ventilation and mitigating actions are likely to be required *(high confidence).*
- Many factors influence the level of CO_2 measured in a space so monitors should be used as a broad guide to the environment rather than to define specific “safe” thresholds *(high confidence).*
- CO_2 monitors are relatively low cost and are likely to be the only viable tool that can enable building occupants and managers to easily evaluate their ventilation. CO_2 monitoring can have two benefits:
    - Use by building owners and managers to help identify poorly ventilated or overcrowded spaces where further actions need to be taken *(high confidence).*
    - Use by occupants to actively manage existing ventilation including balancing the need for good ventilation alongside thermal comfort, moisture, energy use and noise control. This may help reduce overventilation of buildings in winter which leads to significant occupant discomfort and increased energy use (medium confidence).
- CO_2 monitoring is an aid to understanding and managing ventilation, but it is not a mitigation measure itself and may require further action to be taken. The use of CO_2 monitoring does not mean other COVID-19 controls can be reduced *(high confidence).*

Enabling sustained improvement in ventilation

- Mitigating poor ventilation is most important in spaces where multiple people interact over longer periods of time; these are likely to normally pose greater risks than very short duration airborne exposures *(medium confidence).*
- Use of CO_2 monitors to support active management of ventilation is only likely to be successful in settings with appropriate and useable ventilation provision and when introduced with appropriate information and support that is specifically tailored for the group of users who will intervene in response to the CO_2 measurements *(high confidence).*
- Successfully deployment will include co-design of approaches with building managers and users that considers the diversity and knowledge of users and provides information to enable users to both understand the technology and to take effective actions *(high confidence).*
- Further actions are likely to be needed to improve ventilation in many buildings *(high confidence)*. These may include: education on the importance of ventilation; guides/tools aimed at businesses to enable them to make more effective checks; training for industry to ensure they are competent at assessing ventilation systems and checking compliance; financial incentives or grants to enable businesses, landlords and public buildings to improve ventilation in an energy efficient way

- There may be a need to overcome reluctance in organisations to investigate or report their ventilation due to fear of liability or concerns that mitigations may be costly or difficult *(medium confidence).*

Opportunities for Evaluation of Ventilation and Monitoring Approaches

- The technology for CO2 monitoring is well developed and can be readily deployed, but there are substantial knowledge gaps which would benefit from studies to assess CO_2 monitoring in practice:
    - Effectiveness of using CO_2 monitoring to enable sustained improvements in the indoor environment, including the behavioural response of different users.
    - Relative effectiveness of using different display methods (e.g. alarms, "traffic lights" or direct CO2 values) to provide information to occupants.
    - Success of application in different types of spaces such as workplaces, education and public spaces.
- There are multiple knowledge gaps surrounding ventilation which the application of CO2 measurement and monitoring may help address:
    - Assessment of ventilation compliance, provision and effectiveness across the UK building stock, including evaluation of performance-based regulation.
    - Strategies to enable long term improvements in ventilation and indoor air quality alongside addressing the need to minimise carbon emissions.
    - Improved design tools to predict and verify building environmental performance in use.

Supporting Evidence

Brief context on the rationale for ventilation and CO2 monitoring

The SARS-CoV-2 virus can transmit at close range (aerosols and larger droplets), through the air via small aerosols and via contaminated hand and surfaces. Ventilation should be applied as part of the hierarchy of risk control and is effective against airborne transmission (beyond ~1.5- 2m). The rationale for ventilation is set out in a previous EMG paper[1].

There is growing consensus that inhalation is likely to be more important than fomite transmission in most settings; WHO[2] and CDC[3] have recently updated their advice on transmission to highlight the importance of aerosols at close range and longer distance in addition to droplets. Aerosol transmission is implicated in many super-spreading outbreaks[4-7]. Risk factors for airborne transmission include: duration of time spent in a space; activities that may generate more viral aerosols (singing, loud talking, aerobic exercise) and low ventilation rates.

CO_2 monitoring provides an approximate means of assessing the likely effectiveness of ventilation in indoor settings where the only indoor CO_2 source is occupant exhaled breath. CO_2 levels are not a direct measure of risk of exposure to SARS-CoV-2 virus, and the concentration of CO2 in a space does not give a direct measure of safety from an infection control perspective. Further details on the factors that determine CO_2 concentrations in a space are given in Appendix A.

Although monitoring of occupant generated CO_2 can provide a useful indicator of the ventilation rate and the air quality in a room it is also not a formal measurement of either. A CO_2 concentration cannot indicate the air quality in a room when air cleaning methods such as HEPA filtration are used that do not themselves remove CO_2.

CO_2 monitoring is widely used, alongside temperature and moisture measurement, to provide automatic control for both mechanical and natural ventilation systems. However, a very large number of buildings rely on natural ventilation controlled by occupant actions. In these settings stand-alone monitors with a visible display are suggested as a possible option for enabling occupant-led management of ventilation; these are the primary focus of this paper.

Current effectiveness and understanding of ventilation

There is limited understanding and awareness of ventilation and a lack of good data on the effectiveness of ventilation in most UK buildings.

CO_2 monitoring is likely to be a helpful technology for identifying risk to prompt and inform behaviour change.

There is currently very little quantitative data on the quality and effectiveness of ventilation across most building types in the UK. However, there is evidence pre-pandemic to suggest that large numbers of buildings may have ventilation that is sub-optimal, or have been operating ventilation provision sub-optimally, from a health and wellbeing perspective.

Evidence from studies of housing shows even many new buildings do not meet building regulations ventilation requirements[8]. People in the most socially deprived areas are more likely to have poor indoor environments including issues with ventilation, damp and mould, and lower ability to heat their home effectively[9].

In public and commercial premises poorer ventilation may stem from the absence of systems, neglected systems, a lack of awareness or a lack of resources. This includes older buildings that will have been built to previous standards, or before standards were introduced, and buildings which have been altered or adapted. Evidence of performance gaps between standards and compliance suggests that some new buildings may not be achieving current standards[10].

Improving ventilation is possibly more of a challenge for smaller businesses who may not have dedicated facilities managers or the resources to make significant changes. There may also be issues with the degree of understanding of specialist HVAC companies who give conflicting advice depending on their source of advice around COVID transmission. There may be some resistance from some building owner and operators due to concerns about liability if monitoring indicates sub-optimal conditions.

Site visits over the past 12 months suggest a general lack of awareness of ventilation and that many organisations don't consider it effectively in risk assessments. Experience from visits suggests that in sectors where ventilation is an important part of production (e.g. clean environment) there tends to be tighter control and much better understanding of what systems do. However, ventilation in areas like break rooms and changing rooms may be less effective than in production areas.

A survey of 2000 people conducted for the Hands Face Space Fresh Air campaign indicated that there is lower awareness of fresh air as a COVID-19 mitigation (75%) compared to the other aspects of the campaign (face 81%, hands 87%, distance 83%), and that only 50% recognised that windows should be opened regularly[11].

There are multiple concerns that may affect the ability to ventilate a building well, including thermal comfort, energy use, noise and security (see section 3). A small amount of data measured in schools suggests that the recommendation to open windows has significantly improved ventilation in many classrooms during 2020/21. However, feedback from schools suggested there was a challenge with balancing ventilation and temperature over winter months as most rely on opening windows.

Ventilation is invisible; people find it difficult to determine what is good ventilation and to know or agree when to take action such as open/close the windows. CO_2 monitoring allows the indoor environment to be "seen".

1. *Is there any evidence to suggest that ventilation rates or CO2 values previously stated should be altered, particularly in the light of new more transmissible variants?*

The epidemiological evidence to date suggests that ventilation rates recommended previously are still likely to be appropriate, and the focus should remain on improving ventilation in spaces which are poorly ventilated rather than further improving spaces that are already considered well ventilated.

This should continue to be reviewed as further evidence emerges, particularly on transmission of new variants.

There is evidence that some variants are more transmissible than others including B.1.1.7 which is the dominant strain in the UK. Variant B.1.617.2 has been classed as a Variant of Concern and there is some early evidence to suggest this may also be a more transmissible variant.

Nervtag have considered the biological mechanisms for increased transmissibility of B.1.1.7 and concluded that the increased transmissibility is most likely due to higher viral load and/or a lower dose-response. There is no evidence of increased survival of the B.1.1.7 variant on surfaces or in air[12].

There is no evidence that there is any change to the mode of transmission for new variants, however a higher viral load/lower dose-response suggests transmission by all routes could be higher. This may change the importance of different transmission modes in some settings, and if there is more virus emitted and/or infection can occur with a smaller amount of virus this could mean that airborne transmission risks are higher than with previous variants.

Vaccinated individuals who become infected are likely to have a lower viral load than unvaccinated infected individuals, suggesting that transmission by all routes could be lower[13].

The EMG Sept 2020[1] paper suggested ventilation rates recommended in current and recent UK building standards and industry guidance were likely to be adequate in most settings; this is generally a supply of outdoor air of around 10 l/s/person (leading to around 800-1000ppm CO_2, see appendix D). Where ventilation rates were regularly below 5 l/s/person (usually >1500 ppm CO_2) it was recommended that steps should be taken to improve ventilation as a priority. In spaces where aerosol generation could be higher (e.g. where exercise takes place, there is continuous talking or there is a high chance of infectious people being present) or where spaces are occupied by a small number of people (<5) for a long period of time such as a working day, higher ventilation rates to maintain CO_2 concentrations below 800 ppm are recommended.

EMG Jan 2021[14] paper indicated that ventilation may be a more important control for new variants and greater attention should be paid to identify and mitigate risks in poorly ventilated places. Increasing ventilation rates where feasible and practical to do so was considered a reasonable precaution. This advice is still prudent, particularly in areas of the UK with high numbers of cases of a variant, settings where there are large numbers of people or if nationally prevalence increases significantly again.

Several countries have introduced CO_2 monitoring in response to the pandemic and made recommendations around ventilation rates and CO_2 concentrations (appendix C), however there is not yet any published evidence on the effectiveness of these strategies in mitigating transmission. Most countries suggest that values around 800-1000ppm indicate ventilation is adequate. In some countries different values are applied to different settings, for example in Japan 1500ppm is recommended as the upper value for school settings.

Most reported outbreaks which implicate ventilation provide limited data to evaluate the environment. However, from data provided on room sizes, occupancy, activity levels and estimated ventilation rates it is feasible to estimate that expected CO_2 concentrations in some of these spaces would be over 3500 ppm, and likely over 5000ppm (Table 1).

Table 1: Estimated CO_2 concentrations that would likely have been measured in three outbreak cases

				Ventilation								
	Room Volume (m3)	Occupancy	Duration (h)	ach	l/s/p	l/s	Respiratory activity	CO2 generation cm3/s/person	Steady state CO2 (ppm)	CO2 conc (ppm) at end of event	Time to 95% steady state (h)	Notes
Skagit Choir (4,5,15)	810	61	2.5	0.3 - 1.0	1.1 - 3.7	67.5 - 225	Singing	6.4 ± 0.5	4375 ± 2275	2855 ± 885	6.5 ± 3.5	Singing increases breath rate by 165% +- 13%
German meeting room (6,16)	189	13	9	0.2 - 1.0	0.8 - 2	10.5 - 42	breathing/ talking	5.4 ± 0.6	4940 ± 2950	4330 ± 2340	9.4 ± 5.65	Naturally ventilated with windows closed during meeting. Assume infiltration at 0.2 - 0.8 ach
Fitness centre Hawaii (7)	190	11	1	0.5 - 1.5	2.4 - 7.2	26.4 - 79.2	vigorous aerobic excersise	26.2 ± 2.7	8170 ± 4410	4145 ± 1105	4 ± 2	room volume not known, assume 5m floor to ceiling, doors and windows closed, assume 0.5 - 1.5 ach

2. What level of variation in CO2 readings would be expected in a space due to uncertainty/reliability of measurement, variations in ventilation (air distribution), age, and activity, and what are the implications of this for monitoring?

CO_2 variation within a space and positioning and accuracy of sensors can easily result in variations in measured values of 200ppm or greater.

CO_2 measurements should be used as a broad guide to the ventilation and indoor air quality (IAQ) within a space rather than treating values as a "safe threshold".

If CO_2 bands are recommended as a guide for occupants and building managers, these should be sufficiently wide to account for this variation.

The CO_2 concentration gives an indication of the fraction the indoor that is exhaled by its occupants; the rate of CO_2 added to a space increases with the number of occupants, their respiratory activity, and their body mass, and the rate of removal is solely dependent upon the ventilation rate.

Variation within a space: Data from multiple studies shows that measurements within a space vary substantially over the course of a day due to changes in numbers of occupants, occupant activities and ventilation settings, including whether windows are opened or closed. Diurnal fluctuation in outdoor CO_2 values (can be up to 50-100ppm or greater in some large urban areas[17], may also influence indoor values.

Historical school data (pre-pandemic) shows substantial seasonal variation with spaces that are over 1500ppm in winter recording values below 1000ppm in summer[18]. In many cases this suggests that these spaces are able to be ventilated well but are not because either the system is set to provide lower ventilation rates or the occupants are not ventilating (e.g. windows are shut), potentially to manage thermal comfort. Data measured and modelled spatially shows that CO_2 levels within a room can easily vary by 200ppm or more within a space that is nominally well mixed[19]. Measured CO2 in a naturally ventilated office shows that ventilation behaviour affects this variability, with greater variation on days with windows shut[20].

Appropriate sensor location is important, and monitors positioned at different locations within the room could result in different conclusions being drawn about the ventilation within a room. Sensors should ideally be placed at breathing height and away from windows, doors or ventilation openings. Sensors should also not be placed in very close proximity to individuals. Simulated data does indicate that at locations near the walls, where CO_2 sensors are typically located, the range of variation within the interior of the room can be almost fully represented. Values that are particularly low (<500ppm) or high (>1500ppm) can be checked by moving the position of the monitor before taking action.

Influence of occupant emission rates: CO_2 concentrations in a space, like viral concentrations, depend on the emission rate from occupants, which in turn depends on their metabolic rate and age. Emission rates are lower among young children[21,22] and are slightly lower in women compared to men. High activity levels can result in CO_2 emission rates over 4 times those when people are sedentary[21]. This can have a substantial impact on the measured CO_2 concentrations in a setting for the same ventilation rate, and highlights the rationale for recommending lower CO_2 concentrations in spaces where high levels of activity are carried out; the emission of virus from an infectious person is also likely to increase with breathing rate.

Transient variation. Precedents exist in UK health and safety regulation for averaging CO_2 however this is defined in terms of UK workplace exposure limits which are constructed with the intent of being enforceable. UK school ventilation guidance[23] refers to daily average concentrations of carbon dioxide measured during the occupied period (09:00-16:00). For settings in which occupants typically reside for shorter durations average concentrations determined over shorter time periods could be considered. Figure 1 plots data measured in two naturally ventilated classrooms Illustrating the difference between instantaneous data, hourly averaging and daily averaging.

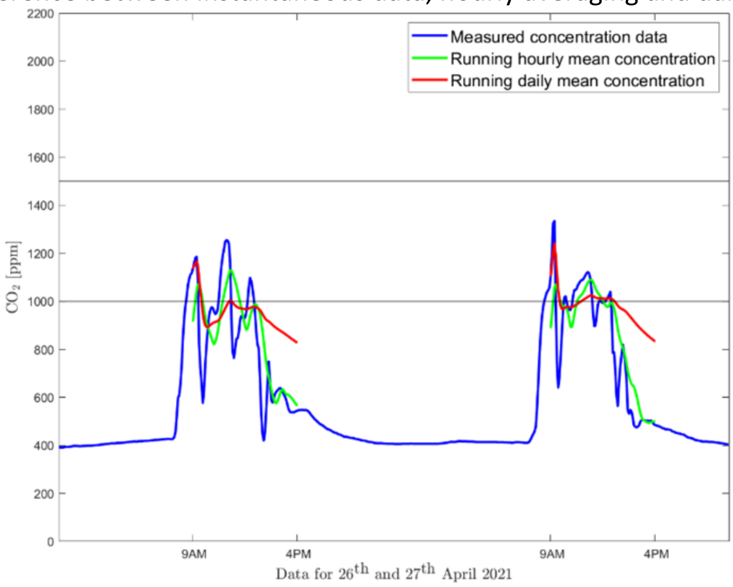

Figure 1: Carbon dioxide concentrations in a classroom with uncontrolled natural ventilation. The instantaneous CO_2 concentration are plotted in blue, during occupied hours[17] running hourly mean concentrations are plotted in green and the running daily average (i.e. since 09:00) are plotted in red.

The appropriate averaging period depends on the purpose of the CO_2 monitoring. Decisions on the effectiveness of ventilation in a space will need to be made on hourly or daily means rather than instantaneous readings; a short duration higher value may result from temporary higher occupancy or occupant proximity to the sensor and is not likely to indicate inherently poor ventilation. Shorter duration averaging is likely to be needed for managing ventilation where short-term actions (e.g. opening a window), are intended to result in an improved balance between greater dilution of indoor pollutants and thermal comfort is needed.

Suitability of spaces: CO_2 monitoring is best suited to high occupant density spaces (e.g. schools, offices) where the indoor concentration is usually noticeably above background and individual variations in CO2 emission have less influence on the measured data. In larger spaces and spaces with higher ceilings it cannot be assumed that the air is fully mixed and CO2 monitors may be less representative (see appendix B).

Table 2: Suitability of CO_2 monitoring in different types of spaces

Characteristics of space	Examples	Suitability of CO_2
Small spaces up to 125m^3/ 50m^2 Occupied by a consistent number of people for >1 hour	Domestic settings where there is more than one person, small offices and meeting rooms, hospital patient rooms	Can be used, but results should be treated carefully as concentrations may be influenced by occupant variability
Small spaces up to 125m^3/ 50m^2 Occupancy is transient and varies over short periods	Changing rooms, small retail, circulation spaces	Unlikely to give reliable readings so and data should be treated with care
Mid-sized spaces 125 – 800m^3/ 50-320m^2 Occupied by a consistent number of people for >1 hour	Larger office and meeting rooms, classrooms, restaurants/bars, some retail spaces, some indoor sports (low aerobic activity)	Often well suited to monitoring as the higher numbers of occupants provides more reliable values. May need to adjust for activity in some settings
Mid-sized spaces 125 – 800m^3/ 50-320m^2 Occupancy is transient and varies over short periods and/or occupant density <1 person/20m^2	Some retail spaces, larger circulation spaces,	Can be used, but results should be treated carefully as concentrations may be influenced by occupant variability
Large spaces over 800m^3/ 320m^2 Occupied by a consistent number of people for a well-defined period of time	Large retail spaces, concert venues, large places of worship, airport concourse, larger sports halls	May be appropriate for monitoring in the occupied zone, but less likely to be well mixed and hence may require multiple sensors to provide meaningful information
Large spaces over800m^3/ 320m^2 Occupancy is transient and varies over short time periods	Large atria, rail concourse, shopping malls	Unlikely to give reliable readings so data should be treated with care

Accuracy of meters: Accuracy depends on a range of factors including sensor types, need for self-calibration (a stable base level of CO_2), contamination (dust, chemicals), sensor drift. Sensors that do not use NDIR (Non-dispersive infra-red) technology should be avoided as they do not directly measure CO2, but infer CO2 concentrations by measuring VOCs, a method which can be very inaccurate. Sensors using NDIR technology are widely shown to give more reliable readings. Sensors typically have an accuracy of +/-50ppm but this can vary by model and be influenced by factors such as temperature and altitude. It is often more appropriate to measure CO2 concentrations relative to the background level rather than the absolute value in order to manage differences in sensor calibration offset.

3. *Is there any evidence that CO_2 monitors can be effectively used by building occupants to manage ventilation in buildings? What are the barriers and facilitators to effective use in different settings?*

Evidence suggests that CO_2 monitoring with visual displays is more likely to lead to improved ventilation than just providing guidance.

CO_2 monitoring is likely to enable occupants to overcome or reduce many of the barriers to enabling good ventilation.

There is limited data on evaluation of acceptability of CO_2 monitoring as an intervention and uncertainty whether CO_2 monitoring can lead to long term behaviour change.

There is not clear evidence on whether displaying CO2 in terms of a measured value, "traffic light" or simple indicator is more appropriate. There is also no clear evidence whether providing other information (e.g. temperature) is also useful for occupants.

Pre-pandemic, several studies conducted in homes, offices, classrooms and controlled experimental settings show that occupants normally open windows in response to temperature[24-26]. In school settings studies show that teachers and students opened windows when warm[27,28] but not in response to poor air quality[25], and that during cold and inclement weather window opening is infrequent because of thermal discomfort due to cold air and draughts[29]

Analysis from shared offices suggests there are complex social determinants that influence window opening and thermal control including social norms, human interactions and the degree of separation between the occupant and the building control[30] and that people will put up with discomfort to maintain relationships with co-workers[31].

Studies that have considered the use of CO_2 monitors are dominated by schools. Heebøll et al[32] compared several classroom interventions and indicated that in the classroom with visual "traffic light" CO_2 monitor windows were opened for longer but there was little reduction in CO_2. An unpublished school study showed that when the automated ventilation system was switched off and a visual CO_2 monitor that displayed CO_2 measurements was provided as an alternative CO2 levels increased suggesting windows were not opened. Two studies[33,34] used a "traffic light" based visual feedback monitor and both showed increased window opening, and similar findings have been seen with a device with a warning light[35]. Studies also showed the enhanced ventilation during the heating season was at the expense of energy[36] and temperature in the room[34]. Recommendations to open windows without the use of a visual monitor were ineffective in all the studies, however this was pre-pandemic when the perceived occupant risks would have been lower.

Evaluation of the acceptability and usability of sensors is very limited. Wargocki and Da Silva[33] asked pupils in their school study to rate the quality of the indoor air and the use of the CO_2 display using “smileys” and indicated that they liked the display. Sustained behaviour change is not clear from the published studies, Most of the studies were all over a short period of time (~1 week), although one over 12 months indicated that pupils may have become accustomed to the device and forgot to pay attention to it[32]. They suggest that a larger or animated display, or one with an audible signal may help occupants pay attention to it over longer periods of time.

The introduction of other technologies for managing the built environment may provide useful insights into expected behaviours with CO_2 sensors. Experience with smart thermostats indicates that those with strong environmental attitudes and technical skills used devices more effectively to enable energy-conscious behaviours[36]. Studies on promoting energy efficiency behaviours indicate that providing normative feedback to enable comparison with other environments/people is more effective at changing behaviour[37]

CO_2 monitoring is recommended in a number of environments, including within the UK. New build schools have the ventilation specified based on CO2 levels with measurement suggested as part of all automated systems[17]. An assessment of ventilation and IAQ in new built homes in Scotland found generally poor levels of ventilation in bedrooms, occupants were generally unaware of poor IAQ and ventilation habits were generally driven by thermal comfort[26]. As a result, the 2015 edition of Scottish Building Regulations were revised to require that a CO_2 sensor is installed in the master bedroom. There is not yet any evaluation of this change. The recent consultation on the UK Future Buildings Standard includes a recommendation to incorporate CO_2 monitoring with a visual indicator in offices.

Application of CO_2 monitoring during the pandemic has been widely suggested, with several countries making recommendations on CO_2 concentrations (Appendix C). In some cases, these are lower values than recommended in building codes. Some countries have also used highly visual display screens in some public spaces[38]. However, there has not yet been any evaluation of the success of any of these approaches in improving ventilation, changing public behaviour, or reducing transmission rates.

In many settings there are competing requirements which have a very strong influence on whether occupants will effectively ventilate a space, particularly where it is naturally ventilated and requires occupants to open windows, doors or vents. As illustrated in Table 4, CO_2 monitoring can potentially enable many of the barriers to providing good ventilation (Table 3) to be managed and in some cases overcome. Barriers to use of CO_2 monitoring focus on practicalities of delivering, understanding and using the technology more than inherent issues with the indoor environment.

Table 3: Barriers and Motivators for ventilating buildings

	Barriers	Motivators/Facilitators
Ventilation (in the absence of CO_2 monitoring)	• Lack of awareness of the importance of ventilation • Lack of awareness that ventilation is poor • Poor outdoor air quality • External noise • Ventilation system noise • Adverse weather	• Habits • Remove moisture, smells • Domestic activities, cooking, clothes drying, bathing • Presence of mould, damp • Clear and accessible mechanisms, controls.

	• Thermal discomfort • Draughts • Concerns over energy consumption, affordability • Agency to take action if there are issues with ventilation – who controls/agrees use (occupants, building manager etc) • Security/ privacy/safety concerns • Need to exclude (or contain) birds/animals/insects	• Clear and appropriate advice on ventilation • Concern over indoor air pollutants • Warm indoor/outdoor temperatures • Concerns over infection transmission • Awareness of the importance of ventilation for wider health and wellbeing • Clear regulations or agreements concerning roles and responsibilities for maintaining ventilation • Mitigations for barriers (e.g. acoustic baffles, provision of barriers/screens to prevent bird/animal/human entry/exit).

Table 4: Barriers and Motivators for use of CO_2 monitoring for effective ventilation.

	Barriers	Motivators/facilitators
Use of CO_2 monitoring	• Understanding of the meaning of the sensor reading by different groups • Potential for fear that a space is "unsafe" if meaning of readings are not well communicated • Need for help on selecting sensors and installation • Understanding of who is responsible for the CO_2 monitor • Maintenance/calibration of monitors • Agency to take action – who controls the installation and use, including training (occupants, building manager etc) • Concerns of liability from building owners/managers • Potential supply chain issues especially for large scale roll out • Risk of limited long term engagement with technology, particularly post-covid	• Access to the sensor data – visual indicators on the devices, apps and web portals. • Potential to manage thermal comfort, and ventilation together to limit cold environments • Potential to allow intermittent ventilation to minimise additional energy costs and ingress of outdoor pollution. • Awareness of and ability to respond to other air quality issues (some sensors measure other pollutants too) • Mechanism for identifying spaces where additional actions are needed • Tool to demonstrate risk assessment has been done appropriately • Ability to provide visual display to demonstrate environmental quality to employees/students/public • Wider potential to educate public/school children around air quality and health

4. *What are the factors that would need to be considered in messaging and support for implementation to enable CO_2 monitors to be used by different groups of people (e.g. public, employers, employees, students, landlords) to their best effect? Are there any other practical approaches that can be taken to enable individuals and organisations to ensure they have effective ventilation?*

Messaging and support needs to be tailored to the particular group of people and the action/behaviour that is intended.

Different approaches will be needed to support facilities managers and engineering professionals compared to those who use the space.

Co-created strategies to build Capacity, Opportunity and Motivation are likely to be needed to enable sustained improvement in ventilation.

Unpublished data from longitudinal self-report surveys in the general public indicate that despite positive attitudes to use of ventilation it is still not reliably used for prevention of Covid-19 infection and often not reported by public facing establishments in their statements on Covid Secure Mitigation Measures taken (even if ventilation may well have been considered)[39,40] -- an 'intention-behaviour gap' that suggests a need to provide better support for implementation[41].

While CO_2 monitoring may offer a valuable means of prompting better implementation of ventilation, it is important to appreciate that enabling people to use CO_2 monitoring effectively for ventilation requires a complex intervention[42] that will need to successfully target different behaviours in different populations and contexts. For example, relevant populations and contexts include workplaces, educational and residential settings, homes and public spaces. Target users include managers, technical support staff, employees, students, landlords, homeowners and the general public.

Behaviours include: acquiring, fitting maintaining and calibrating suitable monitors; regularly checking monitors and taking appropriate action; identifying and addressing any barriers to effective ventilation by target users (including providing education and instructions); consideration of appropriate communication mechanisms, e.g. visual indicators on the monitors, information on mobile apps, web portals.

CO_2 monitors can provide a valuable indicator of a potential risk that requires action, but it is vital that they are deployed appropriately and that users understand the limitations of this indicator. Evidence from the study of alarms in other contexts (e.g. clinical settings) shows the importance wherever possible of applying human-factors design principles to design an integrated compete alert system or philosophy: clear alert criteria; visibility, comprehensibility and layout of monitors; guarding against multiple false alarms; guidance on appropriate response[43].

The principles outlined in the SPI-B paper on 'Sustaining behaviours to reduce SARS-CoV-2 transmission' [44] can be usefully applied to all the behaviours required to implement effective use of CO_2 monitors. Table 5 is adapted from that paper and provides some illustrations of likely elements of a successful public health implementation programme, which will require a multi-layered, multi-faceted approach.

To create initial motivation it will be necessary to create messaging that can convince all target users that good ventilation is necessary, beneficial and achievable without unacceptable costs[45] in terms of other important priorities such as comfort, safety, health, energy use and cost. To sustain behaviour in the longer-term it will be important to create environments and habits that automatically prompt appropriate action without the need for mental effort, and such that monitoring and remediation becomes normal, easy, attractive and routine[46].

Education programmes and accessible instructions will be needed to ensure all target users understand how to deploy and maintain CO_2 monitors, what the readings mean, what response to take, and what to do if the ventilation cannot be effectively managed. Training and instructions will need to consider diversity in users, including their resources, roles and responsibilities, social/cultural expectations and norms, background technical knowledge and capabilities.

Training and instructions will need to be tailored to the particular type of user and what they are likely to be using a CO_2 monitor for. For example guidance for building facilities managers who may be using CO_2 monitors to identify poorly ventilated spaces will have a different focus and is likely to assume a different technical background capability to guidance for building occupants who would use CO_2 monitors as an active day-to-day tool to manage ventilation.

The degree of agency that people have in a space needs to be considered in the strategy for deploying approaches such as CO2 monitoring. In a social space (e.g. pub, restaurant, gym) a customer may have limited ability to take actions but can chose whether or not to visit the setting, while an employee may have more agency to take action but is unlikely to be able to choose to leave a space.

It is important that messaging is developed as part of a wider hierarchy of control for managing COVID-19 risks in a space to avoid giving either false reassurance or inadvertently suggesting that a space is hazardous. CO_2 monitoring to improve ventilation must be part of a package of measures and doesn’t imply that other controls can be reduced.

The APEASE approach[47] - Acceptability, Practicability, Effectiveness, Affordability, Side-effects, and Equity – is likely to be beneficial in designing and implementing CO_2 monitoring interventions.

Table 5: Illustration of some methods of building Capability, Opportunity and Motivation[48] for use of CO_2 monitoring to manage and improve ventilation

Capability Build and sustain an understanding of the benefits of ventilation (especially for infection risk management) and how to achieve it using CO_2 monitors, through: • Creating multichannel information and comms campaigns for workplaces, educational settings, venues, landlords, general public, to explain why and how improved ventilation can reduce transmission. • Providing education on the benefits of ventilation and IAQ (including for infection risk management) right across educational settings from schools to HE and professional training for the HVAC sector. • Providing toolkits, training resources and instructions that are accessible and easy to use by those intended to implement CO_2 monitoring to improve ventilation. • Providing information that enables people to place monitored data and risk into context to take proportionate actions, and doesn’t create unfounded fears that a space may be “dangerous”

Opportunity Ensure that all sectors of society and organisations work together to maximise opportunities for improved ventilation, by: • Providing practical guidance, regulatory, and financial support for the use of CO_2 monitors and for actions to improve ventilation when necessary in home, work, leisure and transport environments. This may need to include support/grants to enable professional assessments of ventilation and retrofit of new systems. • Ensuring all concerned have clear roles and responsibilities to be able to agree and implement appropriate actions to improve ventilation when necessary. • Building strong norms for good ventilation and improved IAQ.
Motivation Ensure that people and organisations are motivated and prompted to achieve better ventilation, by: • Using messaging to increase understanding of benefits of ventilation and create confidence that barriers can be easily overcome. • Co-creating specific community engagement initiatives with minorities and marginalised social groups to address their particular concerns and challenges. • Providing training and resources to build habits and automatic routines that will sustain behaviour in the longer-term without requiring conscious effort; for example, checking the monitor/ventilating the room when first entering it / leaving it / during breaks / when the device prompts attention. • Identifying co-benefits and opportunities by relating ventilation to the wider narrative and regulatory framework on air quality, climate change and sustainability. For example, the use of IAQ monitoring in schools offers potential for wider learning around the influence of the built environment on health and energy.

Research and innovation gaps and opportunities

Given the limited evidence-base for CO_2 and other IAQ monitoring as an effective intervention to improve indoor environments a programme of research and assessment in practice is required to:

a) understand the perspectives, and contexts of different users, including their existing mental models of airborne risk and its control[49].

b) co-design and optimise communications, toolkits and implementation packages to meet their needs and preferences.

c) use experimental methods to establish the cost-effectiveness of these interventions in achieving better ventilation over a sustained period over a range of different settings.

d) evaluate the suitability, usability, and durability of the technology design (e.g. data display, use of alarms/alerts, appropriate sensitivity) to establish the right design parameters for different settings.

Mixed methods evaluations are also needed to understand mechanisms of change and context effects, for example which of the required behaviours are / are not implemented effectively in which circumstances and why.

There is a substantial gap in understanding of ventilation effectiveness and indoor air quality across a very large proportion of the UK building stock. There is a need to build a more detailed picture of ventilation and air quality across domestic, workplace, social spaces, healthcare spaces and educational spaces to understand potential COVID-19 risks as well as wider understanding of the exposure to indoor pollutants on health. The events research programme is likely to yield insights into the benefits that CO2 monitoring can bring in evaluating ventilation and occupancy in a range of sports and cultural venues (appendix B).

In response to this information, innovation is needed to enable long term improvements in ventilation and indoor air quality alongside addressing the need to minimise carbon emissions, particularly in existing buildings[50]. This includes both technology solutions and improved design tools to predict and verify building environmental performance in use.

Appendix A: Further context on CO2 monitoring

The SARS-CoV-2 virus is expelled via respiratory particles in exhaled breath while talking, coughing and breathing. Whilst the virus itself is not easily detectable in these particles, CO_2, also produced in exhaled air is a measure which may help assess the degree to which surrounding air contains the products of respiration. It is important to recognise that the way in which CO_2 diffuses, mixes and is removed from the air is different from the way in which viral particles travel, decay and deposit.

The removal of CO_2 from a space is solely dependent on the ventilation rate, defined as the volume of outdoor air provided per unit of time. Given enough time, a constant CO_2 emission rate, and a constant ventilation rate, the indoor concentration will reach a steady state. This steady state concentration is independent of the space volume, but the time taken to reach it is dependent on the space volume. The removal of aerosols that may encapsulate virus is influenced by the ventilation rate, but it is also dependent on the rate these particles deposit on surfaces (which depends on particle size) and the biological decay rate of the virus. This difference in the removal mechanisms means that a CO_2 concentration cannot be used to indicate the concentration of virus laden aerosols in a space. CO_2 levels are therefore not a direct measure of risk of exposure to SARS-CoV-2 virus, and the concentration of CO2 in a space does not give a direct measure of safety from an infection control perspective.

CO_2 is a useful proxy for ventilation and occupancy but without further information on the space or the people within it, it can be difficult to differentiate between factors; a low CO_2 value could indicate acceptable ventilation, occupancy levels that are lower than those for which the ventilation system has been designed, or a large space where the CO_2 has yet to reach the steady state concentration. CO_2 concentrations will rise in a room even when occupants are wearing face coverings, but the face coverings will reduce the emission of the virus. Although monitoring of occupant generated CO_2 can provide a useful indicator of the ventilation rate and the air quality in a room it is also not a formal measurement of either. A CO_2 concentration cannot indicate the air quality in a room when air cleaning methods are used that do not themselves remove CO_2.

The effect of CO_2 on human health, in the concentrations seen in indoor environments (typically 400-3000ppm) does not pose a health hazard. There is evidence mainly with respect to office workers and school children that at ventilation levels leading to CO_2 concentrations above ~2000ppm for extended periods occupants may feel slightly drowsy and their cognitive performance may be decreased. A study on airline pilots has shown that artificial exposure to CO_2 concentrations of 1500 ppm and 2500 ppm reduced their performance on flight simulators, demonstrating a direct effect of the CO_2 itself on performance, independent of ventilation[51]. It has been shown that exposure to a CO_2 concentration of 3000 ppm leads to increased headaches, sleepiness, fatigue, and concentration difficulties, which may pose safety risks for example for operators of heavy machinery[52]. Improving indoor air quality with respect to CO_2 and other indoor pollutants is likely to be beneficial beyond the immediate impact of increasing ventilation with fresh air to reduce risks from the pandemic.

UK regulation of exposure to hazardous substances includes a workplace CO_2 exposure limit of an 8-hour exposure to an average concentration of 5,000 ppm, or a 15-minute exposure to an average concentration of 15,000 ppm[53]; such exposures are unlikely in most cases where human respiration is the predominant source of carbon dioxide, although as noted in Table 1 may be possible in very poorly ventilated settings.

CO_2 monitoring is widely used, alongside temperature and moisture measurement, to provide automatic control for both mechanical and natural ventilation systems (e.g. demand controlled ventilation). Such systems will provide a ventilation system response to particular set points and are well recognised to be able to provide effective ventilation and balance this with thermal comfort when designed and operated correctly. However, a very large number of buildings do not have any form of automated control and rely on natural ventilation controlled by occupant actions, usually to open windows, doors or vents or use controls to operate fans. In these settings stand-alone monitors with a visible display are suggested as a possible option for enabling occupant-led management of ventilation; these are the primary focus of this paper.

Appendix B: Summary of relevant initial findings from CO2 monitoring during the Events Research Programme:

- Very large venues or buildings need to be considered in context as a set of different spaces, all of which may experience different ventilation rates and occupancy depending on their use. This can lead to large variations in exposure within the building or venue and affect specific risk of transmission for people, depending on how long they spend in each type of space. Managing crowd densities and occupancy levels throughout, are a key component of managing the risk.
- Large public spaces cannot be assumed to be fully mixed and it is useful to divide the spaces into different zones based on use and occupancy, and to monitor them at a higher resolution. At large venues it was necessary to place several CO_2 monitors in every large space within the venues to understand the ventilation of these environments, and the cumulative exposure to exhaled breath experienced by people distributed in different zones within those spaces. If these were monitored with only one CO_2 monitor, the measurements could lead to a significant overestimation or underestimation of overall ventilation rates and poor understanding of the risk of transmission.
- In addition to ventilation rate, the *distribution* of air within a space, or ventilation effectiveness, is a key parameter when assessing the risk of airborne transmission. The nature of many events and the design of some public spaces means people are crowded together which inhibits the free flow of air around the occupied zone. Hence, CO_2 sensors in some zones may show acceptable levels, whereas those in others can show much higher values, indicating an abundance of stale, exhaled air, which cannot easily be replenished with outside air.
- A useful measure of the spaces as a whole, can be given by presenting both average values and maximum values.
- CO_2 concentrations can exceed those previously recommended by SAGE EMG in large venues with high occupancy, whether these were naturally or mechanically ventilated. In almost all cases this occurred for a short time in transient spaces, but where an appropriate ventilation or crowd control strategy is not in place, it was found that such a situation can persist for over an hour up to several hours, potentially increasing the risk of transmission in those spaces.
- During the events, occupancy data obtained from video cameras demonstrates a close correlation with CO_2 levels in the space (which can be seen to increase before an event, reduce during the event and increase again at intervals).
- In areas with transient occupancy the CO_2 monitoring data gives an indication of the variability in the number of people in a space, potentially helping to identify areas of crowding.

- Across the entire set of live events it was found that in specific zones within venues where there were higher crowd densities, for example in queues near toilets or concessions, near bars or other congregation points, maximum CO_2 levels may be up to 400 ppm higher than average CO_2 values and reach higher values than 1500 ppm.
- New approaches to CO_2 monitoring may be considered. Monitoring may not have to be deployed long-term in every building. The events programme demonstrates that useful lessons can be learned from a temporary installation in real world conditions and high occupancy levels, if high resolution monitoring is deployed and the ventilation system of a building is surveyed and analysed in depth; once the assessment is completed, the monitors can be redeployed elsewhere.

Appendix C: CO2 and ventilation guidance in different countries in response to COVID-19

WHO	10 l/s/person, 6ACH in healthcare settings, CO_2 not indicated	https://www.who.int/publications/i/item/9789240021280
USA (CDC)	800ppm is suggested as a broad indicator	https://www.cdc.gov/coronavirus/2019-ncov/community/ventilation.html
EU (ECDC)	800-1000ppm	https://www.ecdc.europa.eu/sites/default/files/documents/Heating-ventilation-air-conditioning-systems-in-the-context-of-COVID-19-first-update.pdf
EU (REHVA)	10 l/s/p or 950ppm over long time, 800ppm over shorter time	https://www.rehva.eu/activities/covid-19-guidance/rehva-covid-19-faq
Germany	1000ppm	https://www.umweltbundesamt.de/en/press/pressinformation/proper-airing-reduces-risk-of-sars-cov-2-infection
France	800ppm	https://www.hcsp.fr/explore.cgi/avisrapportsdomaine?clefr=946
Japan	Japan offices below 1000ppm, schools below 1500ppm	https://www.covid19-ai.jp/en-us/organization/aist/articles/article001
Ireland	800ppm in schools	https://www.hpsc.ie/a-z/respiratory/coronavirus/novelcoronavirus/guidance/employersemployeesguidance/Guidance%20on%20non%20HCbuilding%20ventilation%20during%20COVID-19.pdf

Appendix D: Recommended UK CO_2 values in pre-pandemic guidance

Adapted from BSEN16798 which states CO_2 values for ventilation related to occupant comfort pre-pandemic

Category	Expectation of indoor environmental quality	CO2 above outdoors (ppm) assuming CO2 emission of 20 l/hr/person
I	High	550
II	Medium	800
III	Moderate	1350
IV	Low	1350

CIBSE Guide A, Table 4.2

Ventilation and air infiltration

Table 4.2 Approximate maximum sedentary CO_2 concentrations associated with CEN indoor air quality standards (BS EN 13779)[19]

Classification	Rise in indoor CO_2 concentration / ppm	Default value / ppm	Range in outdoor concentration / ppm	Total indoor value* / ppm
IDA1	<400	350	350–400	700–750
IDA2	400–600	500	350–400	850–900
IDA3	600–1000	800	350–400	1150–1200
IDA4	>1000	1200	350–400	1550–1600

* i.e. concentration rise plus outdoor value

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