Role of Ventilation in Controlling SARS-CoV-2 Transmission
SAGE-EMG

Executive Summary

- Ventilation is an important factor in mitigating against the risk of far-field (>2m) aerosol transmission, but has no impact on other transmission routes (high confidence). The importance of far-field aerosol transmission is not yet known, but evidence suggests it is a risk in poorly ventilated spaces (medium confidence).
- Far-field aerosol transmission depends on the interaction of multiple factors including the viral emission rate, the ventilation rate, the duration of exposure, the environmental conditions and the number of occupants.
    - It is more important to improve ventilation in multi-occupant spaces with very low ventilation rates than in spaces that are already adequately ventilated (high confidence).
    - Activities that may generate high levels of aerosol (singing, loud speech, aerobic activity) are likely to pose the greatest risk; in some spaces even enhanced ventilation may not fully mitigate this risk (medium confidence).
    - Virus survival in air decreases with increasing temperature and humidity. In most environments this effect is likely to be less important than the ventilation rate, however environments with low temperature and low humidity (e.g. chilled food processing, cold stores) may pose an enhanced risk (medium confidence).
- Providing the ventilation rate remains the same, increasing the occupancy of a space increases the probability of airborne transmission by four fold. Exposure risk may be further increased if distances between people are reduced to <2m. (medium confidence).
- Measurements of elevated CO_2 levels in indoor air are an effective method of identifying poor ventilation in multi-occupant spaces. In low occupancy or large volume spaces a low level of CO_2 cannot necessarily be used as an indicator that ventilation is sufficient to mitigate transmission risks (medium confidence).
- Ventilation should be considered as part of a hierarchy of risk controls approach. Source control measures such as restricting or reducing duration of activities and enhanced use of face coverings should be considered alongside ventilation for reducing far-field aerosol transmission risks.
- Assessing ventilation in many environments requires engineering expertise, and mitigation measures are setting specific taking into account the nature of the building and users, ventilation type, length of exposure and activity. Unlike distancing and hand washing, ventilation requirements cannot easily be distilled into one simple approach that everyone can follow.
- Any changes to ventilation must consider other negative consequences including financial, energy use, noise, security and health and wellbeing impacts from thermal discomfort and exposure to pollutants.
- The effectiveness of ventilation in many environments is strongly influenced by user behaviour (high confidence). Clear messaging is needed about the reasons why good ventilation is important and how to effectively operate ventilation systems or achieve good natural ventilation.

Recommended Actions

- Guidance on environmental control for COVID-19 across all sectors should be updated to provide explicit advice on the risk of far-field aerosol airborne transmission, the importance of ventilation, and recommendations on improving ventilation. This should consider the following overarching principles:
  - Ventilation should be integral to the COVID-19 risk mitigation strategy for all multi-occupant public buildings and workplaces. This should include identification of how a space is ventilated and articulation of the strategy that is adopted to ensure the ventilation is adequate.
  - Multi-occupant spaces that are used regularly and are poorly ventilated (below 5 l/s/person or above 1500ppm CO_2) should be identified and prioritised for improvement.
  - Spaces where there is likely to be an enhanced aerosol generation rate (e.g. through singing, loud speech, aerobic activity) should aim to ensure ventilation is sufficient to maintain CO2 concentrations below 800ppm (typically 10-15 l/s/person), and should also include additional mitigations such as face coverings for audiences and restricting the size of groups and duration of activities.
  - Ventilation should be balanced against other factors, particularly thermal comfort. It is recommended that the ventilation strategy should at least achieve the equivalent minimum ventilation rate for the space over the occupancy period as defined in current standards. In naturally ventilated buildings, strategies such as intermittent airing and partial window opening to complement background ventilation may enable this to be achieved. Ventilation rates beyond this should ensure that thermal comfort is not significantly compromised
- Further sector specific guidance is needed for building/facilities managers and professional engineers that sets out ventilation recommendations and practical advice on improving ventilation. This will need to be supported by professional engineering and facilities management bodies and an appropriate campaign for industry.
- A simple public guide on ventilation should be developed with reasons why ventilation is important, practical tips and/or FAQs. This would benefit from co-development with people who are not ventilation experts, and supported by public health campaigns in a similar way to hand washing and face coverings.
- It is recommended to identify where there may need to be financial or technical support to enable individuals and organisations to take appropriate actions to improve ventilation and deal with health and comfort related consequences such as providing adequate heating.
- Research on real-world application of air cleaning and filtration technologies and development of guidance on best practice is urgently needed in order to determine those which are safe and effective.
- Additional analysis is recommended for chilled food processing and other low temperature environments to evaluate the importance of ventilation and environmental conditions on transmission risk
- In the longer term consideration of infectious disease transmission needs to be embedded into building ventilation regulations and associated statutory guidance in the same way that energy, comfort and air quality have been incorporated. Building regulations should identify performance standards and enhanced measures taken to ensure that compliance is achieved in use. As Part F: Ventilation is currently under review there is an opportunity to consider this further and immediately as part of the current review process. Further regulation and guidance may be required to ensure that existing buildings can meet necessary standards.

Summary of Key Findings

Estimates of viral aerosol exposures and transmission risks are made throughout this document using well-established understanding of ventilation in buildings, together with airborne infection risk models. These models are based on well accepted principles but have only had a small amount of validation against outbreak data for SARS-CoV-2 and are currently based on very uncertain data inputs. Results should therefore be treated as indicative of the likely effects based on the best available knowledge at the time of writing, and should not be regarded as predictions.

This paper predominately focuses on public and workplace settings. Ventilation in domestic environments is covered in more detail in a previous paper (SPI-B/EMG MHCLG Housing Impacts Paper 10th Sept 2020).

Q1. How is the risk of airborne transmission impacted by the level of ventilation?

- Ventilation is a key mitigation measure to control the far-field (>2m) transmission of SARS-CoV-2 by aerosols (typically <5-10 micron) between people who share the same indoor space. The measure is not likely to have significant impacts on close range transmission by droplets and aerosols (within 1-2m) or transmission via contact with surfaces (high confidence).
- The relative importance of far-field aerosol transmission compared to other transmission routes is not known. To date, far-field aerosol transmission has been associated with outbreaks in poorly ventilated spaces (<2 l/s/person), particularly where there are activities that increase aerosol production such as singing or aerobic exercise. There is currently no evidence for far-field aerosol transmission in well ventilated spaces (medium confidence).
- For a given activity and viral emission rate, the far-field exposure to viral aerosols is dominated by ventilation rate and time of exposure. Under steady state well-mixed conditions for the same duration, models suggest that exposure to aerosols approximately halves when the ventilation rate is doubled. This effect means the benefits of increased ventilation are most significant where ventilation rates are low (high confidence).
- Size of space is an important factor under transient conditions. In a large space, even when the ventilation rate is low, it will take a long time for the virus concentration to build up and hence short duration exposures may be relatively low risk (medium confidence).
- Multiple other factors influence the risk of aerosol exposure including the air distribution patterns, airflow mixing due to people and flow devices, filtration in ventilation systems, deposition rate, viral decay rate, infector viral load, infector and occupant respiratory activity, occupant breathing rate, and temperature and humidity.
- Flow patterns, particularly in large and complex spaces (e.g. conference venues, theatres, large factories, multi-room/partitioned spaces), may mean that air cannot be treated as fully mixed and assessment of aerosol exposure risk may need more complex airflow models or measurement.
- In most settings the risk of aerosol transmission is likely to be low if the ventilation rate achieves current design standards (medium confidence). For most workplaces and public environments this equates to a flow rate of 8-10 l/s/person based on design occupancy, although guidance for some environments allows for lower flow rates of 5 l/s/person. For some existing and older buildings, systems may not have been designed to meet current standards and additional mitigations may be needed.

- In many spaces ventilation rates are lower in winter to maintain thermal comfort and reduce heat loss. Preliminary models based on historical school ventilation data without interventions suggests that the difference in ventilation rates could increase far-field airborne transmission risk in winter months by 25-35% compared to conditions in September. The reasons for variation in ventilation are not known (low confidence).

Q2. To what degree does the nature of the activities within a setting influence airborne transmission risk and consequently ventilation requirements (i.e. sedentary v active)?

- The viral emission rate is likely to have a significant influence on the aerosol transmission risk. This is likely to vary by several orders of magnitude between people, and evidence from inert aerosol measurements suggests this could be increased by up to 20 times by activities such as singing, loud speech or high aerobic activity (medium confidence). Healthcare and dentistry settings may have an enhanced aerosol generation risk due to aerosol generating procedures.
- For a given number of people, increasing the ventilation rate, carrying out activities in larger spaces and reducing the duration of exposure will all reduce far-field aerosol transmission risk in settings where higher aerosol generating activities take place. For the highest emission infectors, it may not be possible to completely mitigate the risk even with increased ventilation rates (medium confidence).
- Source control strategies including restricting some activities from taking place and implementing face coverings should be considered alongside ventilation measures, and will be the most effective strategy for reducing risk where it is likely that higher aerosol generation will take place.
- Virus survival increases with decreasing temperature and humidity. In most buildings maintaining comfortable temperatures and humidity above 40%RH is likely to be beneficial for reducing risk. However this factor is likely to be less important than the ventilation rate (medium confidence). The virus may survive for significantly longer in low temperature and low humidity environments (e.g. chilled food processing, cold stores) which could enhance transmission risks by all routes including aerosol (medium confidence).
- Aerosol transmission has been indicated as a potential risk factor in outbreaks in chilled environments for food and meat processing. However it is not clear whether transmission in these settings this is due to low ventilation rates, temperature conditions or other behavioural and social factors in these settings.
- Occupant behaviour has a very significant effect on ventilation in many environments, especially those that rely on opening windows, as thermal comfort is the predominate use of ventilation. Many buildings have the capability to provide good ventilation, but do not because users close windows to maintain comfortable temperatures, to prevent noise or pollution ingress, or for security.
- Measures to improve ventilation must consider any other negative consequences, including health impacts. Provision of clear guidance to occupants including explaining why ventilation is important and how to use systems in particular settings is important for ensuring effective ventilation. While it is possible to give some general guidance (e.g for homes), it will be usually be necessary to give setting specific guidance.

Q3. To what degree does the density of people within a setting influence airborne transmission risk and consequently ventilation requirements?

- Increasing the number of occupants in a space increases the likelihood that an infectious person will be present and the number of people who may be infected. On average doubling the occupancy may result in a four-fold increase in the probability of far-field aerosol exposure.
- For the same number of infectious people in a well-mixed space at the same ventilation rate, an increased occupancy does not impact on the individual likelihood of airborne infection unless the density is such that people are within 2m and hence are at enhanced risk of close-range transmission (medium confidence).
- Spaces operating with temporarily reduced occupancy should not reduce the ventilation rate in proportion to the lower occupancy. Ventilation should continue to be provided based on the maximum 'normal' occupancy of the space.

Q4. How can CO_2 sensors be used to understand ventilation effectiveness?

- In the context of SARS-CoV-2 transmission, measurement of CO_2 may be used as an indicator of poor ventilation. In single-zone spaces with more than 20 people, a CO_2 level that is regularly above 1500 ppm (absolute value) is likely to indicate ventilation conditions that pose a higher risk of aerosol transmission. Spaces where there is potential for high aerosol generation should aim for CO_2 at least below 800 ppm, and even this may not be sufficient to mitigate transmission (medium confidence).
- In low occupancy or large volume spaces there is much greater uncertainty in CO_2 measurements, therefore a low level of CO_2 cannot necessarily be used as an indicator that ventilation is sufficient to mitigate transmission risks (medium confidence).
- CO_2 is not a good proxy for transmission risk in spaces where there is additional air cleaning (filtration or UVC) as these strategies remove virus but not exhaled CO_2. It is a less reliable measure in spaces with low occupancy or very large spaces.
- Measurement of CO_2 should be carried out in the occupied area of a room with the sensors located away from windows, doors and ventilation grilles. CO_2 cannot be used as a proxy for ventilation in spaces where there are other CO_2 sources present (e.g. combustion devices). Measurement should normally be made over a period of at least 1 hour to ensure a representative reading. Sensor placement and accuracy must be taken into account when analysing measured data.
- Continuous CO_2 monitoring is not likely to be a reliable proxy for transmission risk in most environments. However preliminary research suggests that in spaces where the same group of people regularly attend (e.g. offices, schools), continuous monitoring may be possible to use as a transmission risk indicator (low confidence).

Q5. What steps could be taken to improve ventilation and what would be needed to achieve this?

- Measures to improve ventilation should not be taken in isolation, and should be part of an approach to risk reduction that considers all transmission routes and applies a hierarchy of risk controls methodology. To mitigate aerosol transmission, ventilation should be considered alongside source control measures.

- Priority should be given to improving spaces which are most likely to result in a high transmission rate: multi-occupant spaces with a higher occupant density which are regularly occupied and where ventilation rates are lower than recent design standards; spaces where there is an enhanced risk of aerosol generation (high confidence).
- Spaces where there is potential for long duration exposure over several hours within the same group (e.g. offices, schools) should ensure occupants have regular breaks, ideally with purge ventilation/airing of the room, to reduce the potential for viral exposure. Further analysis is needed to understand how this approach could be optimised in different settings.
- Increasing ventilation rates may have other negative consequences including increased energy costs, increased carbon emissions, increased ingress of outdoor pollution and reduced thermal comfort. This may include health effects, including enhanced risk of respiratory conditions, from exposure to pollutants and issues with cold and damp for vulnerable groups if there is inadequate heating. Ventilation must be balanced against these considerations, particularly thermal comfort, with sufficient ventilation provided to mitigate the highest risks but without significantly compromising comfort. Heating design in most buildings should account for adequate ventilation rates (as per the Building Regulations), but additional measures may need to be taken in some buildings to ensure that spaces are adequately heated.
- Measures to improve ventilation will be dependent on the particular setting and it is not possible to give a "one size fits all" solution, or a simple rule that everyone can follow. A range of options are set out in Table 1 and further guidance, especially for mechanical ventilation systems is given by CIBSE (2020) and REHVA (2020).
- Any changes to ventilation provision should be designed to comply with the appropriate section of the relevant Building Regulations for the setting. Settings such as healthcare, dentistry and chilled food processing have very specific environmental challenges and requirements. Changes should be considered alongside sector specific guidance and in consultation with an appropriate expert team including building services engineers. It is recommended that those preparing proposals for amended ventilation provision undertake full public consultation with ventilation experts to ensure that guidance is technically correct and reflects current global good practice.
- When considering the renovation of existing buildings to achieve national net zero carbon ambitions, it is essential that the building is viewed as a system and the ventilation provisions are considered as part of the renovation strategy for the building and that the two considerations are addressed in tandem.
- The focus here is on practical measures that can potentially be implemented in existing buildings, in most cases with no or modest capital investment. Longer term strategic actions to improve ventilation across the UK building stock will help to ensure that built infrastructure is more resilient for future disease transmission.

Research Gaps

There remain a substantial number of knowledge gaps which mean that there is a great deal of uncertainty in being able to effectively evaluate aerosol transmission and determine the most appropriate interventions including:

- Lack of data on the viral load in the exhaled breath of asymptomatic and symptomatic people, the size distribution of particles and how this varies with activity;
- Lack of data on the dose-response;

- Limited epidemiological data from outbreaks that allows transmission to be related to environmental conditions to understand the importance of far-field transmission;
- Effectiveness of different ventilation strategies and air cleaning technologies in controlling transmission, as well as practical assessment of safety for different technologies and how and where they should be applied.

Table 1: Summary of options for improving ventilation

Option	Types of settings	Considerations
Increased use of natural ventilation provision (continuous use trickle vents, partial or complete window opening, opening external doors)	Domestic, education, small-mid sized offices	Potential to be effective, but usually relies on user behaviour. Significant issues with winter thermal comfort. May be issues with uncontrolled energy use, noise and pollution ingress. It is more difficult to modulate airflow through doors compared to windows. Actions to improve ventilation should not compromise other aspects of safety and security (e.g. avoid propping open fire doors)
Temporary purge ventilation/airing through intermittent window/door opening or extraction fans	Domestic, education, small-mid sized offices,	Less effective than continuous ventilation, but mitigates many of the issues with comfort, energy, noise and pollution. Most effective during/after higher risk conditions (e.g. when having visitors to home, after the end of a meeting/class)
Breaks or fallow periods between occupants	Any space which is occupied continuously by the same group or sequentially by different people/groups	Allows time for virus to be diluted between occupants which reduces exposure with and between different groups. Regular breaks for continuously occupied spaces reduce viral concentrations and limits build up over time, although may not be effective in small spaces. May be most effective when combined with purge ventilation. Modelling needed to evaluate optimal time for different scenarios.
Maximise outdoor air flow from mechanical systems	Any spaces with mechanical systems	Many systems can be adjusted to provide more outdoor air and recirculate less air, including by altering set points on demand control systems. In colder weather some recirculation may be acceptable if it allows a greater overall ventilation rate without causing thermal discomfort. Turning off the recirculation may lead to a lower ventilation rate because the outdoor air is too cold for comfort, and so the rate of supply is reduced to an inadequate level. Increased outdoor air flow may increase energy consumption and in some cases may compromise thermal comfort unless supplementary heating is provided.
Extended operation of mechanical systems such as extract fans	Any spaces with mechanical systems	Buildings with intermittent extract fans (e.g. that operate with light in toilets) can adjust to run for extended periods. Simple strategy, however the benefits may be fairly modest. Noise may be an issue where systems are run for longer/at higher flow rates
Enhanced filtration/UVC within recirculating centralised HVAC systems	Some spaces with mechanical systems	It may not be possible to upgrade filters to HEPA/MERV 13 within many systems without significant knock on effects. Unlikely to be a significant benefit unless the HVAC system is

		supplying a space with a very high proportion of recirculated air which can't be adjusted to provide fresh air for operational reasons (e.g. chilled environment). These spaces need specific guidance.
Installation of new passive (louvres/air bricks) or mechanical (extract fans, new HVAC) systems	Any spaces	Likely to be a higher cost and longer-term solution ranging from relatively simple vents/extracts to major upgrade of ventilation systems. Need to consider any knock on impacts on flows and pressures in a building.
Use of local in-room HEPA or UVC air cleaning devices	Any spaces	May be a viable solution in spaces where it is difficult to provide good ventilation. Choice of device needs to consider size, flow rate, location, noise and any unintended effects on air quality. Some technologies can be hazardous to health if applied or operated incorrectly. There is a need for better data on real-world application to support these technologies.

Supporting Evidence Summary

Increasing ventilation rate and reducing exposure time are key mitigation measures to control the far-field transmission of SARS-CoV-2 *by small aerosols* between people who share the same indoor space. The measure is not likely to have significant impacts on close range transmission by droplets and aerosols (within 1-2m) or transmission via contact with surfaces. This paper only examines the impact of ventilation on airborne transmission by small aerosols and hence transmission risks stated do not include those from other routes.

Brief background on ventilation

Ventilation is the process of providing outdoor (fresh) air to occupants within a building and removing stale air that may be contaminated. Ventilation is essential for a healthy indoor environment and is widely recognised as a key mechanism for controlling the transmission of airborne infections. Ventilation can be provided through a number of processes, including mechanical ventilation using fans and ducts, natural ventilation which relies on passive flow through openings (doors, windows, vents), or a combination of the two.

All buildings also have some background ventilation through infiltration through gaps (e.g. around door frames, through floorboards and through joints and gaps in the construction). This may be a significant proportion of ventilation but this is uncontrolled, variable, and is not a reliable source of outdoor air.

Air conditioning is the process of cooling, heating, and humidifying air. In some buildings this is linked to the ventilation, with the same units providing outdoor air as well as controlling the environments. In other buildings this is a stand-alone system which simply recirculates and conditions air within a space.

An EMG document on the difference between ventilation and air conditioning has previously been provided (Improving Ventilation 4th May 2020)

Q1. How is the risk of airborne transmission impacted by the level of ventilation?

Evidence for aerosol transmission was set out in a previous EMG paper (EMG-NERVTAG Role of Aerosol Transmission in COVID-19 23rd July 2020)and circumstantial evidence has continued to grow with further cases with a high secondary attack rate reported in a poorly ventilated café (Bloomburg.com) and a bus journey in China (Shen *et al.*, 2020) and a study now reporting detection of low levels of viable virus in air in a hospital (Lednicky *et al.*, 2020). Far-field aerosol transmission has been postulated as the mechanism for super-spreading events and activities with heightened potential for aerosol generation (e.g. singing), but it is not clear how much contribution it makes to community transmission in most settings.

Reported outbreaks where airborne transmission is postulated as the mechanism have reported very low per capita ventilation rates with values in the range 0.5-2 l/s/person estimated; building guidance typically recommends 8-10 l/s/person for most environments based on design occupancy (CIBSE 2016) although some education and retail settings allow for lower rates equivalent to 5 l/s/person (CIBSE 2016, BB101 2018). While there is not a clear threshold value for ventilation rate, evidence suggests that there are more likely to be higher numbers of secondary cases where the ventilation rate is lower than design guidance. There is little evidence to suggest that ventilation needs to be at a rate higher than current design guidance, unless there is a high probability of enhanced aerosol generation.

Airborne transmission risk depends on the concentration of virus in the air in a room, the rate at which occupants in the space inhale the virus, and the duration of exposure (Buonanno, Morawska and Stabile, 2020). In a well-mixed room under steady-state conditions with a constant viral emission rate the concentration of virus is approximately inversely proportional to the absolute ventilation rate (volume flow per unit time) in the room. As such doubling the ventilation rate would roughly halve the viral dose inhaled under the same emission and inhalation conditions. Many exposures will be under transient conditions, where an infector enters a room and the virus builds up over time, or leaves and hence the virus will be diluted by the air over time. This relationship depends on the size of the space as well as the ventilation rate, with build-up and dilution slower in a larger space and where the ventilation rate is lower. Ventilation rate is sometimes expressed in terms of air changes per hour, which is effectively the volume flow rate divided by the room volume.

Exposure to far-field viral aerosols can be estimated through knowledge of viral emission rate and the ventilation conditions, with absolute risk estimated with knowledge of dose-response. The emission rate and dose-response are commonly coupled together through the Wells-Riley model, which uses a parameter "quantum of infection" to represent infectious dose in a similar manner to a concentration in air. This model has been widely used to analyse the influence of ventilation on transmission of infection including TB (Escombe *et al.*, 2008), SARS(Qian *et al.*, 2009) and influenza (De Mesquita, Noakes and Milton, 2020). A number of published (Buonanno, Stabile and Morawska, 2020; Miller *et al.*, 2020) and pre-print (Burridge et al 2020, Jones et al 2020, (Peng and Jimenez, 2020)) studies have considered airborne transmission of SARS-CoV-2 using both the well accepted Wells-Riley approach and a range of exposure models that more explicitly consider the size distribution and behaviour of aerosols.

Data on viral emission rates for SARS-CoV-2 is very limited, however estimates used in modelling have suggested it may vary by several orders of magnitude depending on the individual and their activities. Higher emissions have been estimated from those with a higher viral load in their respiratory fluids (Buonanno, Stabile and Morawska, 2020), those who are coughing (Leung *et al.*, 2020), and with singing/loud speech (Morawska *et al.*, 2009; Miller *et al.*, 2020). Buonanno et al 2020 estimate that a symptomatic SARS-CoV-2 case generally has a viral emission rate of <1 quanta per hour, while high emission rates >100 quanta per hour may occur with vocalisation during light activities. Exposure is likely to be influenced by the breathing rate of individuals which could vary by a factor of 6 between passive sedentary breathing to high exertion aerobic exercise (Adams 1993). Viral decay has a modest impact on exposure; the half-life of the virus in indoor air has been shown to be around 1 hour (van Doremalen *et al.*, 2020) although may be longer in lower temperature conditions. Factors such as aerosol deposition and temperature and humidity have a smaller influence on risk over the timescales of most interactions compared to viral emission rate, breathing rate and ventilation rate. Filtration may be an important factor in reducing viral concentrations environments where air recirculation takes place, either within a stand-alone unit (e.g. in-room air conditioner) or as part of the building mechanical system. The effect on viral concentration will depend on the grade of filter and the proportion of air that is recirculated (Zhang *et al.*, 2020).

Relationships between key parameters that influence transmission risk using a stochastic version of the steady-state and transient Wells-Riley model for a single zone space shown in figure 1 illustrate that risk is dominated by the quanta generation rate, and is likely to be greatest with very low ventilation rates and high aerosol generating activities. Steady state conditions are applicable where the infector has been present in a venue for some time before the exposure (e.g. the shopkeeper is infected and a customer enters), while transient conditions are applicable where susceptible and infected people enter a venue at the same time (e.g. a audience at a performance).

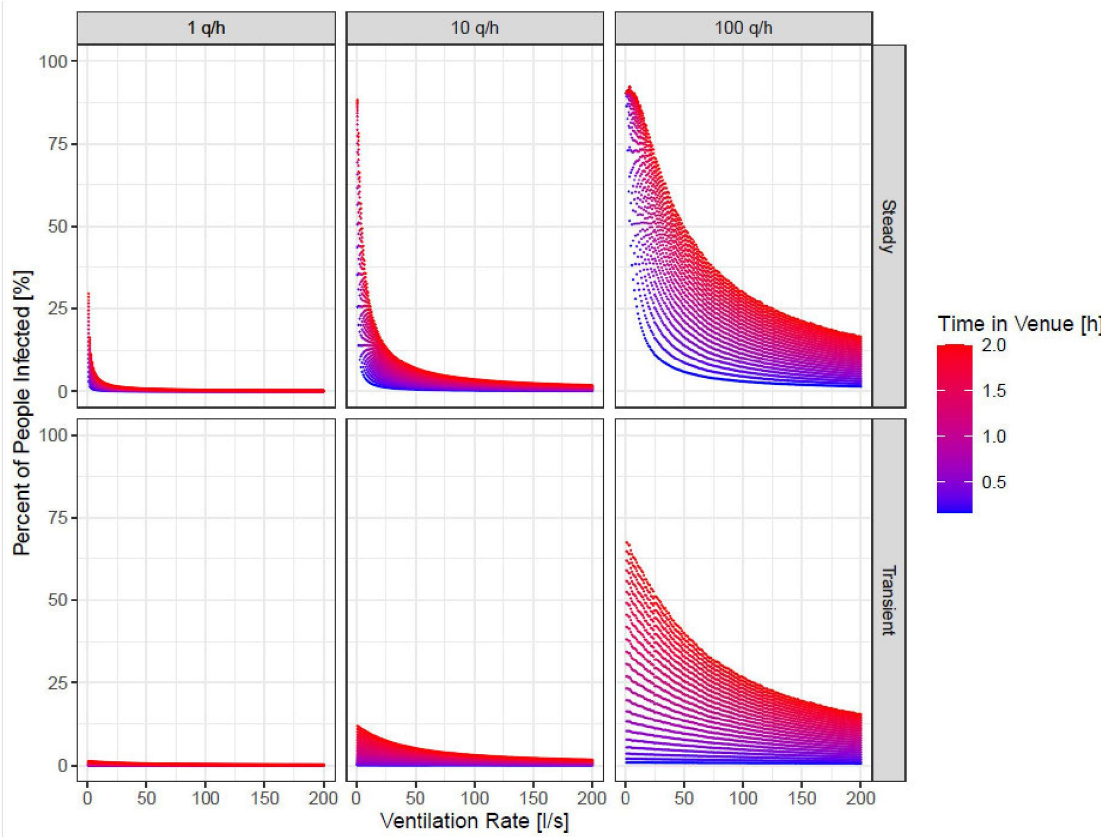

Figure 1: Wells-Riley model showing variation in risk with ventilation rate, duration of exposure, quanta (infectious dose) generation rate and breathing rates (up to 50 people, breathing rates 8-16 l/min, quanta generation 1-100 q/hour).

To consider the influence of typical scenarios, including transient effects, results from an alternative model that considers exposure Relative Exposure Index (REI) (but not dose-response) are shown in figure 2. This is based on work in a pre-print paper (Jones et al 2020) and concurs with analysis in (Buonanno, Stabile and Morawska, 2020). Exposure increases with longer duration, lower ventilation rate and activities that may have enhanced aerosol generation. A ventilation rate below guidance values (e.g. Office vs OfficeLow) can more than double the REI. Large spaces (e.g. a supermarket) mitigate far-field aerosol transmission risk, especially where exposure times are short.

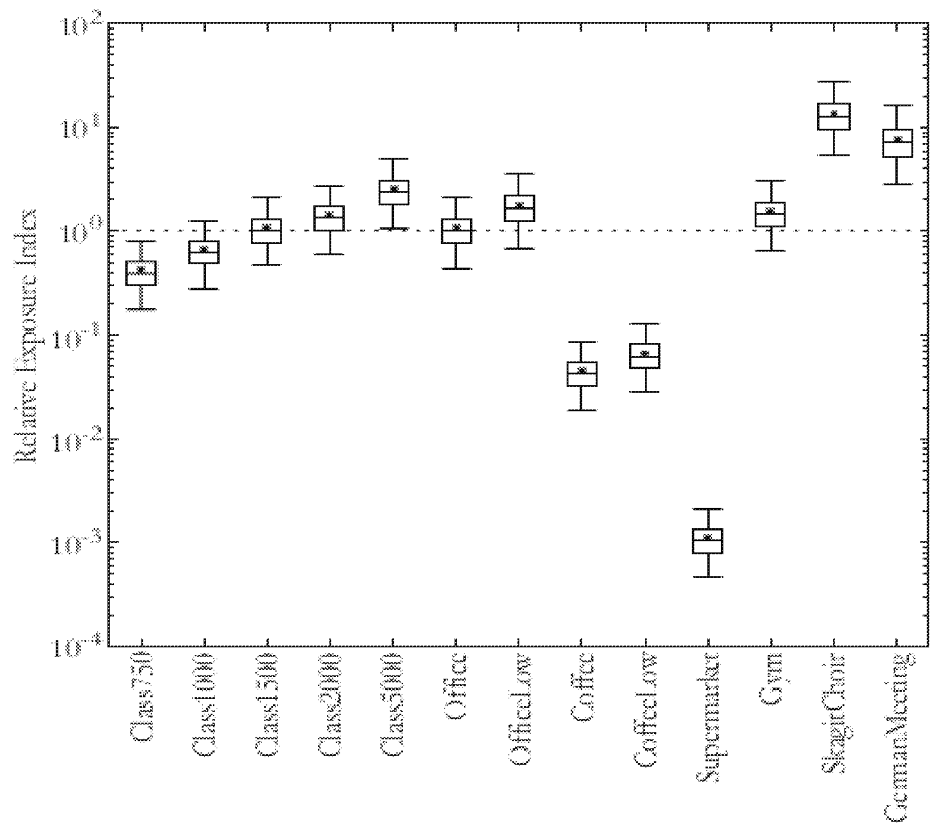

Figure 2: Box plots showing relative exposure risk (compared to a 8 hour office exposure) for a range of scenarios (of varying exposure times) including classrooms, offices, coffee shop, supermarket, gym and two reported outbreaks (Jones et al 2020).

These transmission models assume well-mixed conditions provide a reasonable estimate of the influence of ventilation risk in most small and medium sized spaces, although it should be noted that factors such as thermal stratification and the ventilation system design can result in incomplete mixing (Bhagat *et al.*, 2020). This is particularly the case in large spaces or those that are partition or divided into multiple zones, where a well-mixed ventilation assumption might over or under-estimate the level of risk (Noakes and Sleigh, 2009; Parker *et al.*, 2014). This has the potential for over-estimating risk in occupied time but over/underestimating time for purging depending on the nature of stratification and airflow pattern. These types of spaces require more complex models such as computational fluid dynamics or zonal-network models to evaluate potential transmission risks.

Models of airborne transmission risk are also unlikely to give meaningful analysis of risks in settings where there are small numbers of people and multiple interactions, or where ventilation flows are very variable or uncertain. This is particularly the case for housing where close range interactions and shared surfaces are likely to play a significant role in transmission. Stochastic models may be appropriate to use in settings with small numbers of people who are present for a long period of time such as a hospital ward (Noakes and Sleigh, 2009; López-García et al, 2019)

In many buildings, particularly those that rely on passive background ventilation (eg trickle vents opening windows), ventilation rates vary with weather conditions and by season. Ventilation rates are likely to be lower in winter months compared to summer. This is primarily because both mechanical systems and those that rely on users opening windows/vents are more likely to reduce flow rates to reduce heat losses in colder conditions. Preliminary analysis based on CO_2 data from school classrooms using the approach in Burridge et al (2020 pre-print) suggests that reduced ventilation during the heating season could increase the secondary attack rate due to small aerosol airborne exposure by 25-35% compared to September (Annex 1).

Q2. To what degree does the nature of the activities within a setting influence airborne transmission risk and consequently ventilation requirements (i.e. sedentary v active)?

Aerosol generation

Activities such as singing and loud speech can significantly increase aerosol generation. Data on aerosol particle generation (not virus) in healthy volunteers from (Morawska *et al.*, 2009) suggests a 1:5:30 ratio for breathing:talking:vocalisation. This concurs with data in a pre-print paper (Gregson *et al.*, 2020) which showed 20-30 times increase in aerosol particles with loud singing and loud shouting compared to breathing. Aerosol generation is also associated with some healthcare procedures and is a concern in dentistry. It is not yet clear whether the enhanced aerosol production results in a proportional increase in viral emissions, however evidence from choir outbreaks suggests a possible correlation.

Activities that increase breathing rates may increase generation and inhalation of aerosols. Breathing rate while aerobic exercising can be 6x seated breathing rate (Adams 1993), and Bernardi 2017 suggests that breathing rate increases by approximately 160% when singing. It is also possible that exercise makes individuals more susceptible to infection (Davis *et al.*, 1997), although it is not clear whether this is important for COVID-19.

A model of transmission in the Skagit choir outbreak which resulted in 53/60 people infected (Miller *et al.*, 2020) suggests that the infectious person may have generated up to 1000 times more infectious quanta than those with a lower viral load who are sedentary detailed in (G. Buonanno, Stabile and Morawska, 2020). However, the initial report suggests there were opportunities for droplet transmission from close contact or fomite transmission so the evidence for 100% aerosol transmission is uncertain. Simulations suggest that increasing the ventilation loss rate from 0.3-1 h^{-1} to 5 h^{-1} and reducing the rehearsal duration from 2.5 to 1 hour may have still only halved the transmission rate. Simulations presented in a previous EMG paper (SWI Aerosol and Droplet Generation from Singing, Wind Instruments and Performance Activities 26th Aug 2020) show the potential relationships between ventilation rate, duration, proportion of time singing and transmission risk.

Lower temperature and humidity are both associated with enhanced virus survival in air. Data from laboratory studies suggests that when the temperature and humidity are reduced from 24°C/60%RH to 20°C/30%RH the half-life of the virus in aerosol may increase by over 6 times in dark conditions and 2 times with a UV index of 1. At very low temperatures the half-life may be several hours (Schuit *et al.*, 2020). There is no data on normal indoor light conditions. Aerosol transmission has been indicated as a potential risk factor in outbreaks in chilled environments for food and meat processing. Multiple outbreaks have been reported in such settings with many linked to workplace practices or shared worker housing and transport. However in a number of cases, transmission appears to have happened within a workplace environment at distances beyond 2m. In addition to the cold conditions, chilled food plants may have low ventilation rates, with a high proportion of air recirculated to maintain the cold temperatures. The importance of these different factors is not yet known.

User behaviour

Except in fully mechanically ventilated buildings, user interaction with ventilation provision will have a major impact on its effectiveness. Buildings users will be driven primarily by thermal comfort and are generally unaware of air quality issues except in extreme situations. A number of studies show that actions such as opening windows are carried out in response to feeling warm rather than awareness of indoor air quality. Studies in domestic environments also show a lack of occupant awareness and understanding of ventilation systems, including occupants being unaware of the presence of devices such as trickle vents (Sharpe *et al.*, 2018). People may adjust or block ventilation supplies including covering grilles and vents if they experience cold drafts. Social structures in workplace settings may also influence ventilation behaviours, with ventilation in shared offices determined by multiple factors including "ownership" of windows, a desire not to upset colleagues and the need to negotiate with "gate keepers" such as facilities managers (Snow *et al.*, 2016).

Providing clear guidance and information to users will be an important step in ensuring that spaces remain effectively ventilated. While it is possible to give general guidance that could be applied broadly to environments such as homes, in workplaces and public buildings guidance is likely to be setting specific. This should include how and when to operate ventilation systems and where appropriate to provide information to reassure occupants that ventilation provision is acceptable. Raising awareness of issues of the potential for airborne transmission and the importance of ventilation will be key to ensuring that guidance is followed.

It is also essential that appropriate guidance is provided to facilities managers and building services engineers who may be servicing and advising on ventilation systems. Targeted campaigns by HSE and/or industry bodies such as CIBSE may be needed to ensure that this message is effective.

Q3. To what degree does the density of people within a setting influence airborne transmission risk and consequently ventilation requirements?

Changing the occupancy influences the probability that an infectious person is present and the potential number of secondary cases that may result. However it doesn't fundamentally change individual exposure if the number of infectors that are present and the total ventilation rate is the same. Doubling the occupancy density of a space will therefore increase the probability that one susceptible occupant becomes exposed by four times. For airborne transmission it is the density per unit volume of the space that is important rather than the density/m2, providing the space can be treated as well mixed. The absolute risk will depend on the viral emission rate and the ventilation and activity parameters. Relative risk with occupancy, ventilation rate and size of space are shown in heat maps in Annex 2, which can be used to assess the relative influence of occupancy density.

When distancing is less than 1-2m and is in the breathing zone of an infected person then proximity matters, and infection risk will increase further due to exposure to higher concentrations of aerosols and droplets close to the infected person. This effect is not considered here, and ventilation is unlikely to mitigate this risk.

Regional/Local incidence of SARS-CoV-2 in the population is a factor that may be considered in planning mitigation strategies. When there are more people with the disease there is an increased probability of viral aerosols and it may be appropriate to pay greater attention to building ventilation controls as part of a risk assessment methodology for workplaces and retail settings.

Q4. How can CO2 sensors be used to understand ventilation effectiveness?

Relationships between CO_2, ventilation and infection risk

There are many studies in which CO_2 is used as an indicator of ventilation and IAQ. As CO_2 is emitted by human metabolic processes, levels correlate well with occupancy as a marker for human-generated pollutants. CO_2 is present in the outside air at concentrations between 350 and 575 ppm (0.035 and 0.057%). The level of CO_2 in exhaled breath is around 3.6 – 4.3% (36,000 – 43,000 ppm). Human CO_2 generation rates depend on physiological conditions including age, gender, health and activity (Persily & de Jonge, 2017).

Indoor CO_2 concentration level depends on the number in a given area, their activity level, and the outdoor air ventilation rate per person, Both CIBSE and ASHRAE recommendations for ventilation rates of 8-10 l/s per person in an office type setting correspond to a CO_2 concentration around 1000ppm. In communal areas such as offices a value around 1000ppm is widely regarded as an indicator of sufficient per person ventilation rates to provide perceived good indoor air quality and counter the human sourced emissions including moisture. A review on associations between ventilation rates and CO_2 levels with health outcomes concluded "Almost all studies found that ventilation rates below 10 l/s per person in all building types were associated with statistically significant worsening in one or more health or perceived air quality outcomes" (Seppanen et al 1999). A paper by Wargoki on ventilation in housing identified associations between CO_2 levels and health and concluded "The ventilation rates above 0.4 air changes per hour or CO_2 below 900 ppm in homes seem to be the minimum level to protect against health risks based on the studies reported in the scientific literature."

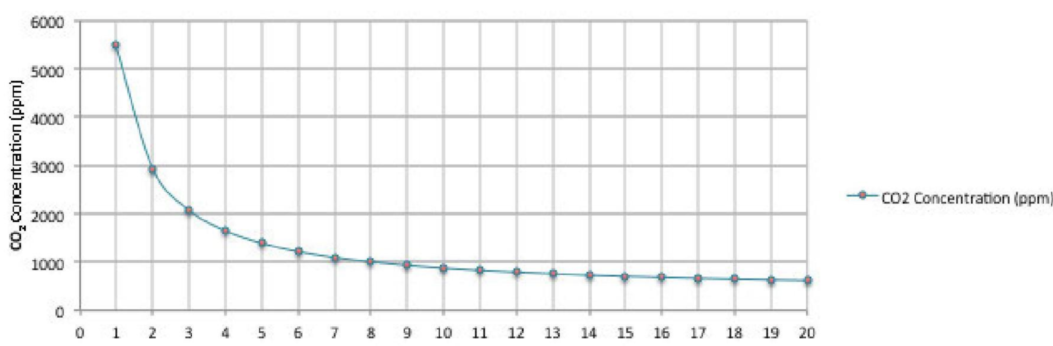

Figure 3: CO_2 vs. delivery rate for an office type setting.

The relationship between CO_2 and infection risk is less well explored than relationships with indoor air quality. A study of ventilation improvements during a TB outbreak in university buildings (Du *et al.*, 2020) showed when CO_2 was reduced to <1000 ppm was independently associated with a 97% decrease in the incidence of TB among contacts. A pre-print paper modelling transmission risk with ventilation shows the CO_2 level corresponding to a given infection risk may vary by over 2 orders of magnitude depending on the environment and activity. However they still suggest that it is a useful metric to assess ventilation (Peng and Jimenez, 2020).

Rudnick and Milton (2003) proposed a version of the Wells-Riley model that uses CO_2 as a marker of rebreathed air fraction, which has been used by a number of authors to explore TB transmission. Measurements of CO_2 can be used with this approach directly to infer the likelihood of airborne infection risk arising. This has been applied to evaluate influenza transmission in a human challenge study (De Mesquita, Noakes and Milton, 2020) and a pre-print paper for SARS-CoV-2 (Burridge *et al. 2020*). This can be done most effectively for spaces regularly attended by the same group of people, e.g. open-plan offices and school classrooms. Table 2 shows results for an open-plan office occupied according to design guidance, and indicates that the secondary cases due to airborne exposure only over a 5 day period with an infector present could range from 0.24 to 35 depending on the ventilation rate and the generation rate of infectious doses (quanta).

Table 2: Likely infections arising from airborne transmission (R-numbers) in an open-plan office (floor plan of 400 m^2 and floor-to-ceiling height of 3.5 m) occupied by 40 people for 8 hrs each day over a 5 day period that one pre/asymptomatic person remains attending work.

Scenario	Vent rate 4 l/s/p	Vent rate 10 l/s/p	Vent rate 20 l/s/p
Quiet desk work, q=1 quanta/hr	R = 0.84	R = 0.42	R = 0.24
Talking sedentary, q=5 quanta/hr	R = 4.0	R = 2.1	R = 1.2
Super-spreading events			
q=20 quanta/hr	R = 14	R = 7.6	R = 4.4
q=100 quanta/hr	R = 35	R = 26	R = 18

Application of CO_2 *as a proxy for infection risk*

A steady state CO_2 concentration indicates the per capita airflow rate in a space but not a gross airflow rate. The relationship between CO_2 concentrations and exposure to virus depends on the number of people, airflow patterns, activity and duration of time in a space. Table 3 shows results from a transient Wells-Riley model for a worst case scenario - a high-density space (30 people at 1.7 m2/person) at quanta generations rates of 1, 10 and 100 quanta/hour (G. Buonanno, Stabile and Morawska, 2020) for up to 6 hours. Results concur with the pre-print by Peng and Jimenez (2020), showing potential for over 2 orders of magnitude difference in risk at the same ventilation rate depending on the infector emission rate. For the majority of cases (1 and 10 q/h) the probability of a secondary case is low and only increases to a level that is likely to lead to a new case when the ventilation rate is not sufficient to keep the CO_2 below 1500ppm and the duration is over ~4 hours. However, when there is high aerosol generating activity (100 q/h), even ventilation that would lead to a CO_2 concentration below 900ppm is insufficient to prevent an average of one new case in only one hour. Annex 2 shows relative exposure heat maps with CO_2 for a range of occupancy, ventilation rates and room sizes.

Table 3: Averaged likely number of new cases in a worst-case occupancy scenario with ventilation rate/ CO_2, quanta generation rate and time (30 people, 150 m3 room, continuous occupancy, 8 l/min breathing, 0.005 l/s/person CO_2 generation).

		1 hour			2 hours			4 hours			6 hours		
l/s/person	steady CO2	1	10	100	1	10	100	1	10	100	1	10	100
1	5373	0.04	0.38	3.59	0.13	1.23	10.25	0.36	3.38	20.92	0.61	5.58	26.17
3	2058	0.03	0.26	2.51	0.07	0.68	6.13	0.16	1.53	12.24	0.25	2.36	16.79
5	1395	0.02	0.19	1.88	0.05	0.46	4.26	0.10	0.98	8.45	0.15	1.49	11.96
10	897	0.01	0.11	1.13	0.02	0.25	2.38	0.05	0.51	4.73	0.08	0.77	6.88
20	649	0.01	0.06	0.61	0.01	0.13	1.26	0.03	0.26	2.51	0.04	0.39	3.70

Models and practical experience indicate that measurement of CO_2 is a useful indicator to identify poor ventilation in the context of airborne transmission, but may not be necessarily an indicator of sufficient ventilation to fully mitigate transmission.

In a space with more than 20 occupants, a CO_2 concentration routinely greater than 1500ppm (absolute level) is considered to be an appropriate marker to indicate poor ventilation or overcrowding regardless of the size of a space, and is therefore likely to be associated with a higher risk of transmission. Spaces where CO_2 cannot normally be kept under 1500ppm are suggested as the highest priority for mitigation.

Settings where there is likely to be enhanced aerosol generation, for example through singing, loud speech or aerobic activity may pose a substantially higher risk. Ventilation rates should aim to maintain CO_2 below 800ppm and the duration of exposure below 1 hour. Even this may be insufficient to fully mitigate transmission, and other measures may need to be introduced.

Use of CO_2 as an indicator for ventilation effectiveness is more difficult in spaces with lower numbers of occupants (<20) due to the increased influence of individual variations in CO_2 generation rate; any measurements in spaces with lower occupancy should be treated with caution. Measurement of CO_2 cannot account for other mitigation strategies such as filtration, UVC air cleaning or the use of face coverings; these strategies remove the virus from the air but not CO_2.

Although it is recommended that priority is given to poorly ventilated spaces, improved ventilation in other spaces may also be beneficial. Longer term actions to maintain CO_2 below 1000ppm may further reduce transmission risk as well as more widely improve indoor air quality for the health of occupants.

As detailed in Annex 1 it may be possible to use CO_2 monitoring as a tool for directly evaluating risk over a longer period of time in some spaces. This is unlikely to be effective in spaces that are transiently occupied by different people or in spaces such as domestic environments where transmission is likely to be dominated by close contact. However it is possible that it could be used in regularly attended spaces such as schools and workplaces. Further research is necessary to evaluate the potential application of the approach for different spaces and to compare modelled results with actual infection rates.

Practical considerations with CO_2 monitoring

CO_2 measurements (Using a non-dispersive infra-red NDIR Sensor) can be a relatively cheap and easy indicator of ventilation in many buildings. However, they should always be used as an approximate guide and never regarded as an accurate measurement of the indoor air unless used as part of a study with appropriate controls. CO_2 concentrations recorded will depend on multiple parameters including: the occupants and their activities; variations in building type, form, ventilation provision, air permeability, weather and external CO_2; the sensor accuracy and calibration; other CO_2 sources; the positioning of the sensors.

To get the most representative reading sensors should be located in the occupied zone of a space, away from doors, windows and vents and at least 0.5m away from people. If a space has additional filtration or air cleaning measures to control virus (e.g. HEPA filter or UVC devices) then CO_2 measurements will not account for these measures and may indicate a higher risk than is present in the space.

CO_2 measurement is already widely used in mechanically ventilated buildings through embedded sensors as a means of controlling ventilation systems, although monitored data is rarely accessed. Stand-alone monitoring could be used by FM/Building managers as part of a process to check ventilation effectiveness.

CO_2 monitoring is also likely to have value in raising occupant awareness of ventilation requirements and has been used to inform user behaviour to improve ventilation. A study in classrooms found that giving users visual feedback using CO_2 monitors increased window opening (Heebøll, Wargocki and Toftum, 2018). However, this requires careful guidance to ensure that users understand the monitoring and take appropriate actions. Threshold values suggested here are approximate guides and should not be rigidly applied.

Q5. What steps could be taken to improve ventilation and what would be needed to achieve this?

Identifying poor ventilation

There is concern that many settings may not be adequately ventilated, given the evidence about the levels of compliance with other aspects of building regulations in England reported in the Independent Review of Building Regulations and Fire Safety carried out by Dame Judith Hackitt (Published May 2018). And prior to this the 'Performance Gap' was increasingly well evidenced (Zero Carbon Hub). Many buildings also have a ventilation strategy that relies on user interaction (e.g. opening windows/vents) and if these are not operated as envisaged it can lead to poor ventilation. User interaction with ventilation is driven primarily by awareness of thermal comfort and concerns about heat loss. Some building typologies (thermally poor buildings and low-income occupants) mitigate against more liberal ventilation.

It is strongly recommended that attention should be focused on poorly ventilated spaces, or where the means of ventilation is not apparent or known. This will provide the greatest benefits without significantly compromising energy or comfort.

Visual inspection provides a first step in assessing ventilation to determine the mechanisms that provide ventilation to a space.

- If there are no mechanical systems (extract fans, air conditioning units, ventilation grilles etc) then the space is naturally ventilated and relies on opening windows, doors, passive vents (e.g. air bricks) and infiltration. If, in addition, there are no windows that can be opened or passive vents it is likely that the space is poorly ventilated unless doors are opened very frequently
- If there are mechanical systems then it is important to check whether these provide outdoor air, thermal control or both. If a system (e.g. a local air conditioner) is recirculating only and doesn't have an outdoor air supply, or a separate source of outdoor air, the space is likely to poorly ventilated.
- While it is not an accurate measure, odour in a space can also give an indication of ventilation effectiveness. A space that feels stuffy or has significant odour is likely to be poorly ventilated. Caution should be exercised in spaces where there are local recirculating air conditioners as these can mask poor air quality, making a space that would normally be stuffy feel comfortable but without providing fresh air.

Measurement provides a more accurate level of assessment. A simple assessment can be carried out using passive CO_2 monitors as detailed above, and use of smoke sticks can provide a visual indication of ventilation flows and dilution rate. For more in-depth analysis, measurement of flow rates through fans/grilles in mechanical systems or use of tracer gas tests can provide a more quantitative assessment of flow rates. It is very likely that more in-depth analysis would have to be carried out by building services engineers.

Strategies to Improve Ventilation

The primary principle for improving ventilation to minimise transmission, is that the level of "fresh" outside air should be maximised and any recirculation should be minimised (or stopped if practical) as the dilution of the internal air will reduce the risk of viral exposure.

A number of online calculators exist to estimate the risk of aerosol transmission in a space Under different ventilation and occupancy scenarios (https://cires.colorado.edu/news/covid-19-airborne-transmission-tool-available, https://rapidqmra.shinyapps.io/Rapid_QMRA/). These should be treated with caution as the calculated risks are based on some uncertain data, however they are able to give an indication of the range of airborne risk that could be expected in a particular setting and how this could be mitigated.

To provide ventilation in a naturally ventilated space, the background provision should be in operation and windows or other openings should be opened. More ventilation will be provided with larger openings and, if available, use of opening windows at opposite sides of the building. It is recognised that providing maximum ventilation by opening all windows fully when outdoor air temperatures are low will be difficult or unacceptable. However, occupants might also note that the rate of supply of air increases with larger temperature difference between the inside and outside, so that windows do not need to be opened as much in colder weather to achieve the same flow rates. It is possible to estimate ventilation rates as a function of open window area on a still day, and there are a number of standard methods to do such calculations (e.g. CIBSE AM10, Jones et al 2016).

Particularly for naturally ventilated or mixed mode ventilated spaces it is possible to "purge" or "air" the space intermittently to facilitate dilution of any virus. Experimental and simulation studies show that short duration airing of a building at regular intervals can be effective at controlling indoor air quality and may provide more acceptable thermal comfort than keeping windows open continuously (Heiselberg and Perino, 2010). Melikov, Ai and Markov (2020) analyse intermittent occupancy which may be accompanied by increased ventilation during breaks as a means of reducing the viral concentration in air, and suggest a 10-20 minute break (fallow time) every hour for a meeting room scenario. The effectiveness of purging ventilation will depend on the design of the space. Using high level windows in winter may be effective for purge ventilation in order to clear indoor air that is warmer than outdoor air. Further analysis would be needed to determine the most appropriate combinations of ventilation rate and occupancy schedule for different settings to provide the most effective control.

While there is no evidence of substantial transmission throughout buildings via mechanical ventilation systems, systems which have significant recirculation may potentially pose a risk. For mechanically ventilated spaces, the amount of fresh air should be maximised and the recirculation minimised as far as systems allow without significantly compromising comfort. This may mean a reduction in any heat recovery. Extract fans in toilets or WC should be running to facilitate air movement during occupied hours. The filters on any air handing units (AHU) should be clean and maintained to maximise airflow, and all ductwork and diffusers cleaned. Proper and adequate maintenance should be carried out on the mechanical ventilation system to ensure that any dampers are set correctly. Fuller guidance is given by CIBSE (2020) and REHVA (2020) on mechanical ventilation systems.

In spaces where there is significant recirculation of air, filters within HVAC systems will offer some mitigation against aerosol being reintroduced to the space via the ventilation (Zhang *et al.*, 2020). The effectiveness will depend on the grade of the filter, and in most buildings the removal is likely to be modest. In some mechanical ventilation systems, it may possible to upgrade filters or to install UVC disinfection systems within the HVAC system. However, both options involve significant capital cost and in the case of filters many systems are not capable of being upgraded without compromising other aspects of performance. These options are likely to only be appropriate in spaces where there is a very low outdoor air flow rate and there is a high risk of transmission.

Portable fans, ceiling mounted fans or recirculating air conditioners will assist air circulation, but will not add to the air change rate or the amount of outdoor air coming into the space. The influence of such systems on transmission risk is not certain. Zonal transmission risk models (Noakes and Sleigh, 2009) suggest that enhancing mixing in a space that is not designed to be mixed can increase exposure to airborne pathogens. This may increase overall risk, but it is only likely to be significant if the ventilation rate is poor; the impact in a well ventilated space is minimal. Studies of particle deposition show that higher air velocities increase the deposition rate of particles (Thatcher *et al.*, 2002), however it is not clear how this will apply to airborne virus and which size particles are influenced the most. Zhao and Wu (2007) suggest that for particles smaller than 5 micrometres, air velocity and surface properties are important, but for larger particles gravity dominates. The spatial distribution of aerosol concentrations can be affected by local air flows and particle size (Parker *et al.*, 2010).

Local air cleaning and filtration may be beneficial for reducing aerosol risks in some spaces, particularly if it is not possible to increase ventilation. These devices typically use HEPA filters or UVC irradiation to remove or inactivate viral aerosols. Such devices are either stand-alone consumer devices which can be readily deployed in any space, or installed in a similar manner to a local air conditioning unit. All such devices will increase the "effective" ventilation rate, however their impact will depend on the volume of the room, the flow rate through the device, and the effectiveness of the device in influencing flow in the whole volume of a room. Noise and emissions from the device should both also be considered, and some devices may pose health hazards if used incorrectly. Use of these devices will not change CO2 concentrations in a room, and hence their impact on the effective ventilation rate will need to be assessed using alternative methods. Further information on air cleaning approaches are given in a previous EMG paper (Summary of disinfection technologies for microbial control 18th May 2020).

Additional measures such as air bricks, louvres, mechanical supply or extract fans can be installed to enhance the ventilation rate in most buildings, however these will require alterations to the building fabric (such as a wall or window fan or even additional roof mounted plant with internal ductwork and ceiling outlets. The wider consequences of any such alterations should be considered including impacts on noise, air quality, energy, thermal comfort and the influence on internal flow paths in the building.

Wider consequences of changes to ventilation

Ventilation has well-established associations with health and has a complex relationship with multiple other factors including energy, noise, air quality and thermal comfort. These relationships are not straightforward and despite a large body of research considering both the human health and building design aspects, there are many aspects that are poorly understood. Increasing ventilation rates may have a negative impact on all of these factors leading to impacts on health, wellbeing, productivity and sustainability. Hence any actions need to consider the unintended consequences. This will be setting specific and dependent on the occupants, the building design and its location.

In the majority of spaces concerns over thermal comfort during the heating season (October – May) are likely to be the biggest barrier to improving ventilation, with increased ventilation especially through opening windows reducing indoor temperatures, increasing cold draughts and increasing heating bills. In many buildings there will be a trade-off between comfort and risk which needs to be carefully considered. Using strategies such as intermittent airing, particularly in naturally ventilated buildings may be a good approach to reduce transmission risks without significantly compromising thermal comfort. If additional heating is required to maintain thermal comfort it is important that safety considerations such as electrical overload, fire risk and trip hazards are considered.

Lower temperatures can lead to other health impacts including higher susceptibility to respiratory infection (Mourtzoukou and Falagas, 2007) and greater risk of mould and damp which can aggravate allergies. Similarly in highly polluted environments, greater ingress of outdoor air pollutants may have a significant negative impact on health, in particular respiratory conditions.

Actions to improve ventilation need to consider the short term challenges and mitigations as well as long term needs. Some negative effects may tolerated on a short-term basis providing they don't cause serious health impacts. However, any more substantial changes must consider the long-term consequences including energy and sustainability.
(Sharpe et al., 2018, Snow et al., 2016)

Practical and regulatory considerations
It is recommended that before any work is carried out on a ventilation system, the user should be aware of how their ventilation system operates and the level of ventilation that is currently in their premises or home, as it may already be sufficient. If the premises ventilation is designed and verified against the relevant section of the devolved administration Building Regulations (i.e. Approved Document Part F or Section 3 of the Scottish Technical Handbook), this may be sufficient, however it may be prudent to have this verified.

Spaces with specialist ventilation or that have particular environmental requirements will require additional consideration. While some of the principles set out in this paper apply to settings such as hospitals, dentistry, chilled food processing and industrial process environments, it is essential that any changes to ventilation are made with consideration of the systems installed and the guidance/regulations that govern them. In many industrial settings here may be positive or negative pressure zones, local exhaust ventilation (LEV) for contaminant control or other systems that are particular to the setting. These will impact on the overall ventilation; LEV that discharges to atmosphere will add to the existing ventilation rate as 'clean' replacement air enters the building/room, but only while it is switched on. Some LEV systems use high efficiency filters and return the air to the workplace. In this scenario, they would increase the effective ventilation rate.

It will be necessary to consider how actions relating to ventilation can be monitored and enforced. As it is difficult to measure/verify ventilation it is unlikely that measures will be easily enforceable. It is suggested that assessment of ventilation is added to the checklists for COVID-19 risk assessments, so organisations have to explicitly show they have considered mitigation of aerosol transmission risks.

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Annex 1: Inferring airborne infection risk from monitored CO2

Whilst CO2 can be used to indicate ventilation rates it can also be used to infer airborne infection risk more directly. For airborne infection to occur a susceptible occupant must breathe in rebreathed air, i.e. air that has already been breathed by another, from an infected individual. Monitoring CO2 enables the fraction of rebreathed air to be directly assessed. Assuming some fraction of the rebreathed air is infected, combining with a measure to assess the infectivity of the disease (the quanta generation rate), and recording over time, provides the probability of infection occurring.

Naturally one has to select a duration over which to assess the probability of infection. This duration is often arbitrary; however, for indoor spaces which are regularly attended by the same group of people day-in-day-out, e.g. school classrooms and open-plan offices, it is reasonable to assume that once an infected individual exhibits symptoms they cease attending. This identifies an appropriate duration since one can assess the likelihood of infection occurring during the pre/asymptomatic period (which for COVID-19 is estimated to be 5-7 days). Hence one can ask the question: what is the likely number of infections that arise from an infected individual attending during one pre/asymptomatic? This can be estimated by monitored occupancy and CO2 levels which accounts for fluctuations in occupancy and provides the R-number for a regularly attended space.

Application to an office scenario is set out in Burridge et al (2020, pre-print) leading to the results shown in Table 3 above. Application to school classrooms is as shown in the Figures below which estimate variations in R over a 12-month period. It should be noted that this work has not been peer-reviewed yet.

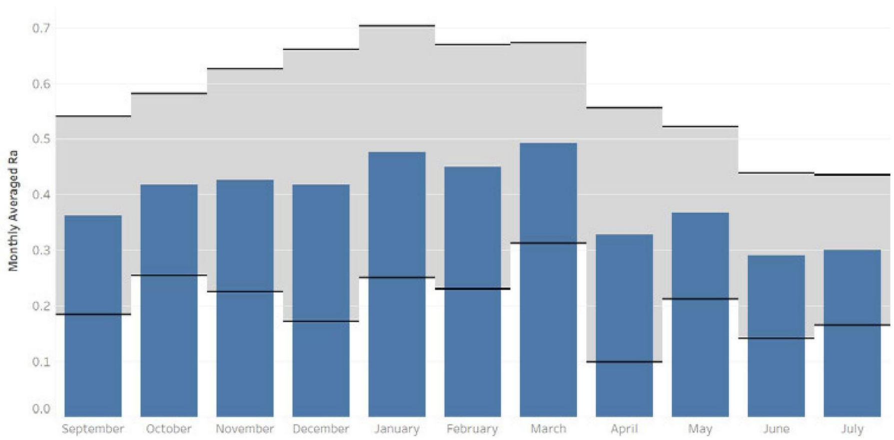

Figure A2.1: Monthly R based on measured CO2 concentrations taken from 39 classrooms within 10 different primary schools, the height of the blue bar represents the mean and the black lines mark one standard deviation above and below. The data assumes asymptomatic airborne transmission (over 5 days) with 1 quanta/hour. Measurements were taken between November 2015 and March 2020 and originate from schools in England, as far North as Yorkshire, as far South and West as Somerset and as far East as Kent, they include a mix of data from schools in urban and rural settings. The data provision from Monodraught Ltd and the iServ database, and the data analysis of Carolanne Vouriot is gratefully acknowledged.

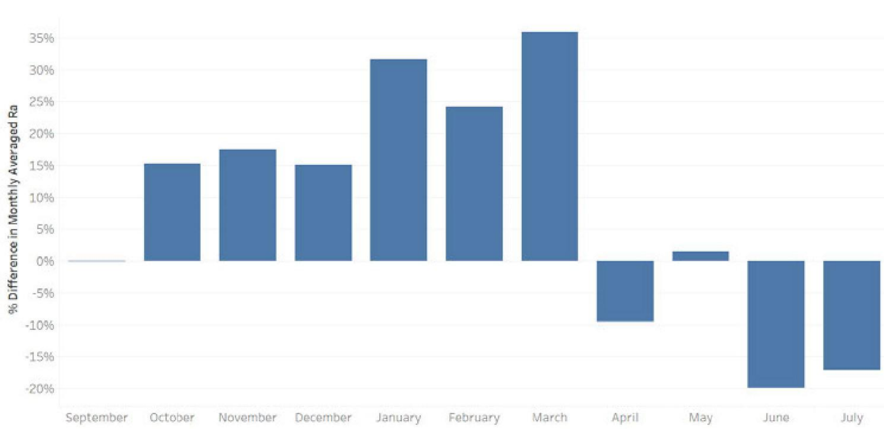

Figure A2.2: Average monthly change in R compared to September for the data shown in figure A2.1.

Annex 2: CO_2 and Relative Exposure Index Heat Maps

In the heat maps a generic space is considered and the transient concentration of indoor CO_2 and Relative Exposure Index (REI) calculated as the time of exposure increases moving left to right on the x-axis. The values are also calculated at increasing space volumes (y axis bottom to top). Each heat map represents an occupancy level and a ventilation rate as indicated. Comparison of the REI and CO_2 heat maps enables a quick indication of how measured indoor CO_2 values may be used in assessing ventilation provision and the predicted REI.

The Relative Exposure Index is derived from a mass balance equation detailed in *Jones et al* (2020) essentially comparing the relative risk of a susceptible individual inhaling a dose of viral genome copies (some of which are viable virus) that deposit in the respiratory tract and could lead to an infection in a described scenario to a reference case. In this instance the reference case with an REI of 1.00 is equivalent to a UK Junior classroom, $148m^3$, occupied for 7 hours, ventilated at 5l/s/p (160l/s) with one infected person present. Serendipitously an REI of 1 is also found for a $600m^3$ office with 20 occupants, ventilated at 10l/s/p (200l/s), occupied for 8 hours. The higher ventilation rate in the latter counters the increased breath rate (and therefore emission rate) of the assumed adult male occupants (males used as worst case, as their breath rate is greater than female at rest). The assumed aerosol emission of viral genome by the infector is based on 75% breathing and 25% talking – as the respiratory activity is related to the aerosol emission rate.

The model is a transient model and assumes that at time zero there is no viral genome material present. There are uncertainties in some of the assumptions used in the model and these are explored further in *Jones et al* (2020). Due to the assumption of a well-mixed space, the model may be less accurate for larger volume spaces.

Individual REI: In this relative risk assessment a single infector is assumed to be present in the test spaces and the exposure risk of a single susceptible individual sharing the space is calculated. The heat maps in Figure 1 show a low occupancy (5 person) space has lower ventilation rates and thus increased risks compared to the reference case, because the ventilation rates are expressed in terms of l/s/person. Providing 10l/s/p for 5 persons occupancy provides a toal of 50l/s which is half the ventilation flow of a 20 person space ventilated at 5l/s/p (100l/s). The REI increases with exposure time and decreases with increased ventilation and space volume. The risk is lower in larger volume spaces as there is a large reservoir of air to dilute any emitted aerosols and it takes a longer time for steady state conditions to be realised. Therefore, for short exposures in large spaces the role of ventilation is less significant.

Event REI: In this relative risk assessment we assume the probability of an infector within a space (ie the greater the occupancy the greater the probability of an infector being present) and the exposure risk to all occupants, ie the probability of an infective dose may be low for the individual, but if there are more individuals in the space the probability that one may receive an infective dose will increase. With respect to the event REI (Figure 2- Event Relative Exposure Index – Shows how the Event REI changes over time and room volume, and in relation to ventilation provision.) the value is lower in the lower occupancy spaces because the probability of an infector being present is low. As the occupancy increases, the probability of an infector increases, as does the chance of a susceptible person receiving an infective dose.

In both the event and individual REI analysis, increasing ventilation reduces the relative risk, as does increasing the volume of the space.

Benefits of a Relative Exposure Index

Because we don't know the emission rate of viral genome by an infected person (because it can vary over an order of several magnitudes), REI does not provide an absolute risk, but enables an assessment that scenario A is less/more safe than scenario B if the same infector was present in both scenarios.

The CO_2 heat maps (Figure 3) show how the CO_2 concentration increases within a space until the steady state concentration is reached. The time to steady state is longer in larger volume spaces. There is a strong correlation with high CO_2 values (>1500ppm) and an increase in REI in both the individual and event level scenarios, the high CO_2 levels are also indicative of poor ventilation flow rates. However, low CO_2 values are not necessarily indicators of good ventilation, for example in poorly ventilated larger spaces low CO_2 values can be recorded for several hours as the time to reach steady state is long. However, the time to steady state for any airborne aerosols in the same space will be equally large, so the low CO_2 values in large spaces over short exposure times are also indicative of lower REI.

In small volume low occupancy spaces (eg 5 occupants in <300m^3) with an infector present the REI is high even when CO_2 levels are <1000ppm as only 50l/s of ventilation flow is required to keep CO_2 below 1000ppm, whilst higher ventilation flows would reduce the REI further.

Jones, B., Sharpe, P., Iddon, C. Hathway, A.E. & Fitzgerald, S. Modelling uncertainty in the relative risk of exposure to the SARS-CoV-2 virus by airborne aerosol transmission in Buildings. *Prepr. Res. Gate* (2020) doi:10.13140/RG.2.2.25874.89283.

Individual Relative Exposure Index

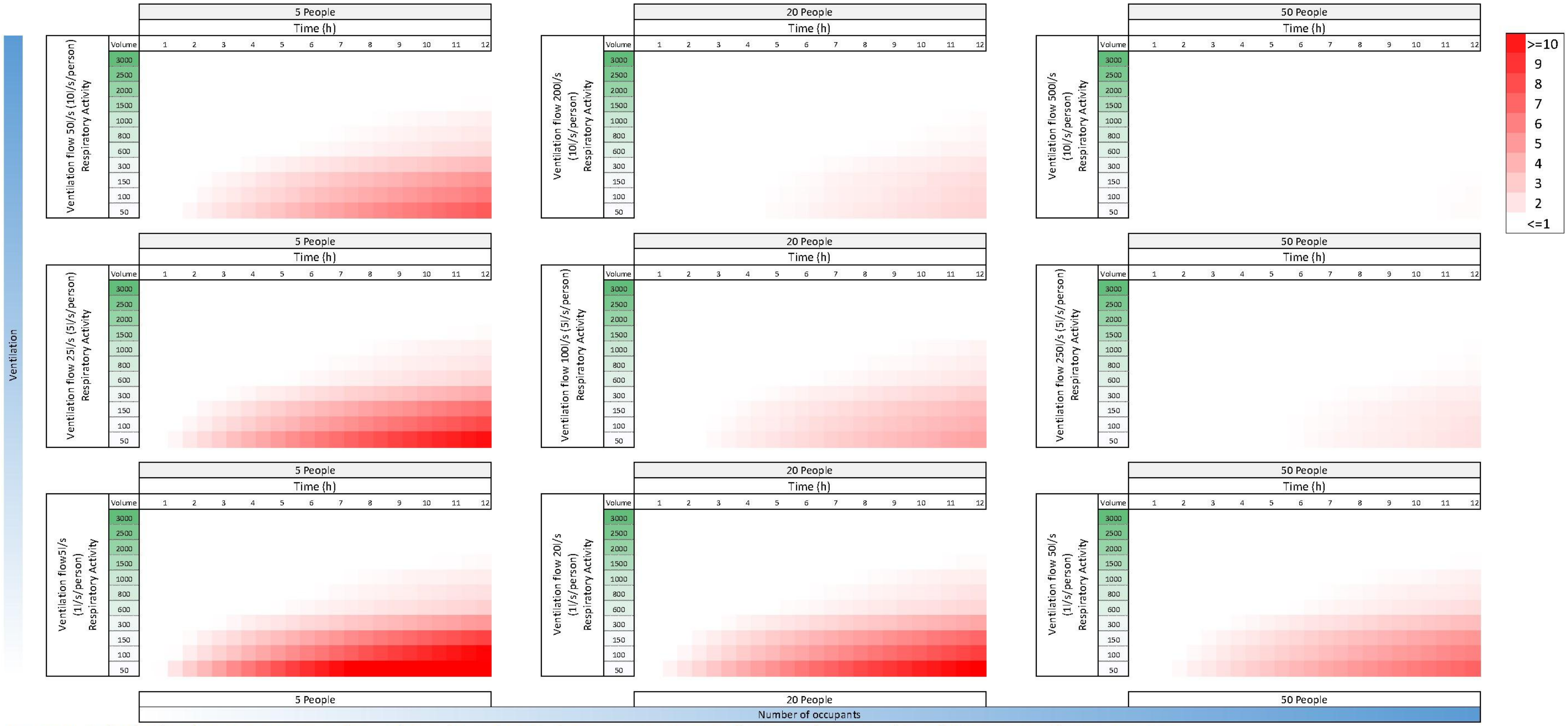

Figure 1- Individual Relative Exposure Index – Shows how the REI changes over time and room volume, and in relation to ventilation provision.

Event Relative Exposure Index

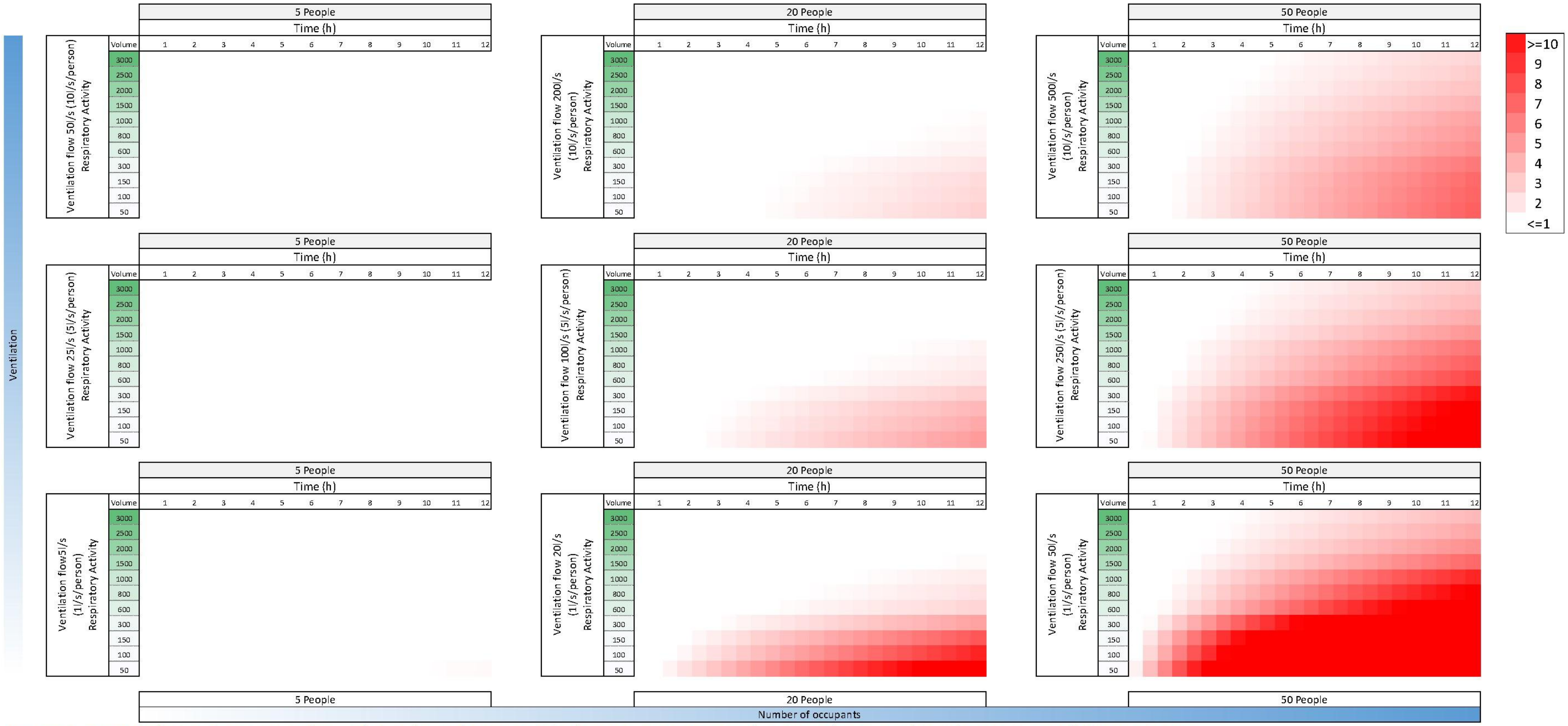

Figure 2- Event Relative Exposure Index – Shows how the Event REI changes over time and room volume, and in relation to ventilation provision.

Indoor Carbon Dioxide Concentration

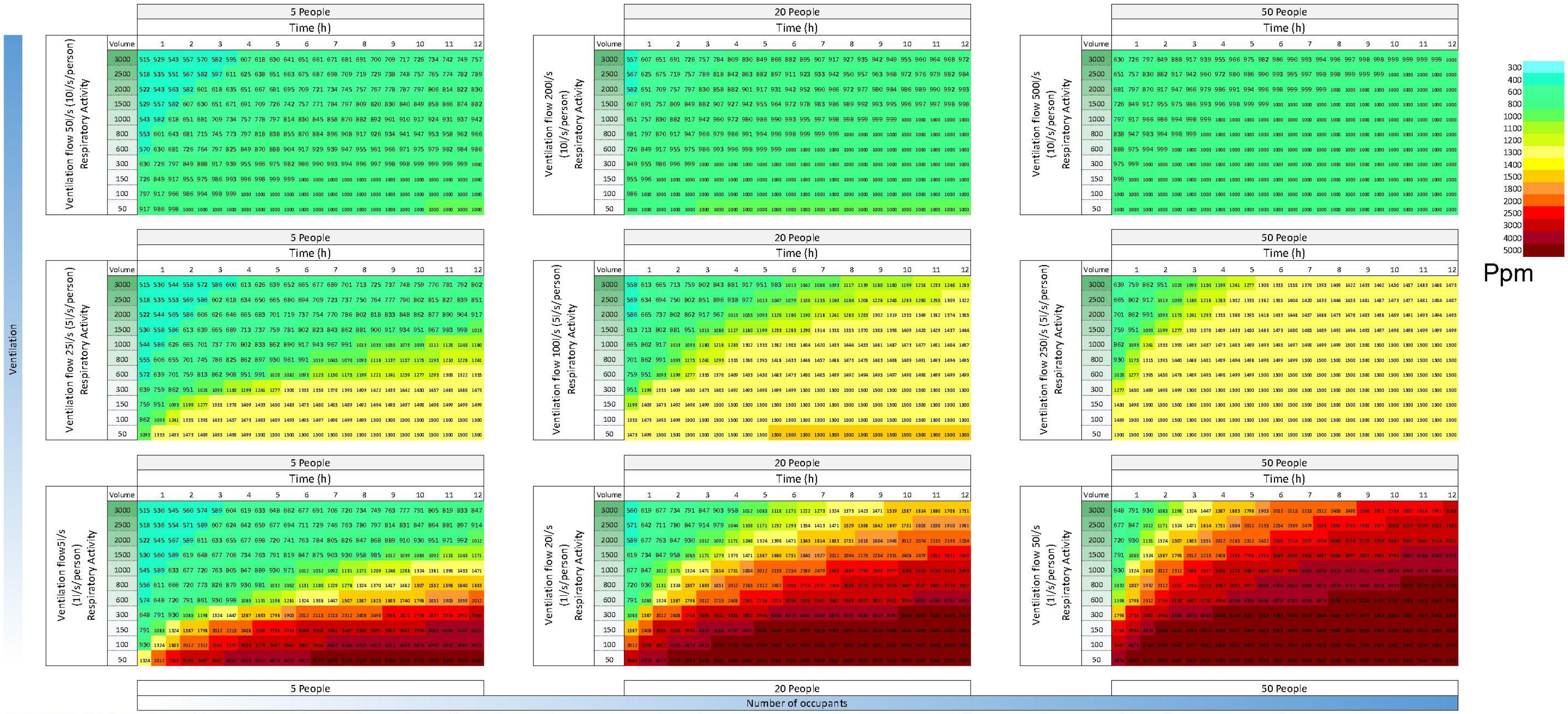

Figure 3- Carbon Dioxide concentration – Shows how the indoor CO_2 concentration changes transiently over time and room volume, and in relation to ventilation provision