Rapid IAQ monitoring at Large scale events
lessons from the Events Research Programme

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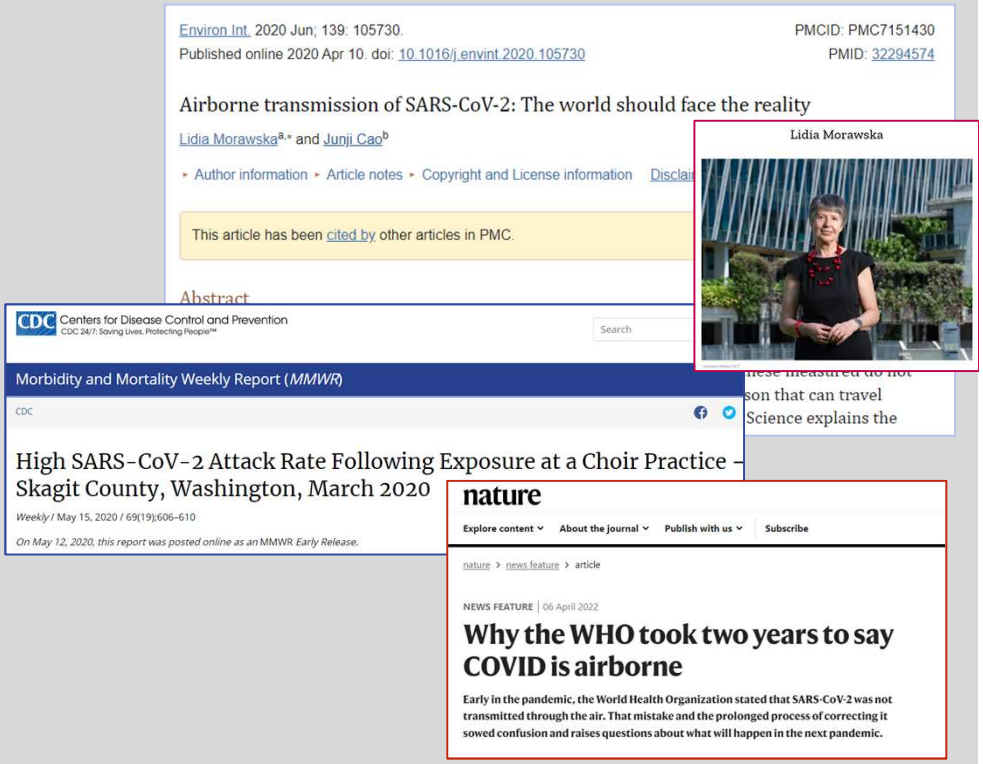
Overview

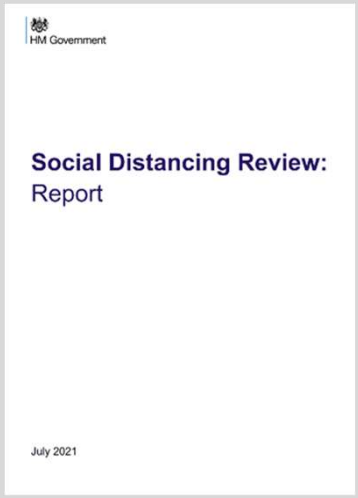
- Context – Airborne Transmission, Widespread Closures, The Events Research Programme
- The problem we were asked to investigate
- Our approach
- Getting organised
- The process: event/data collection, analysis, science board…
  and repeat
- Methods in depth
- Key research outcomes

Airborne transmission is established

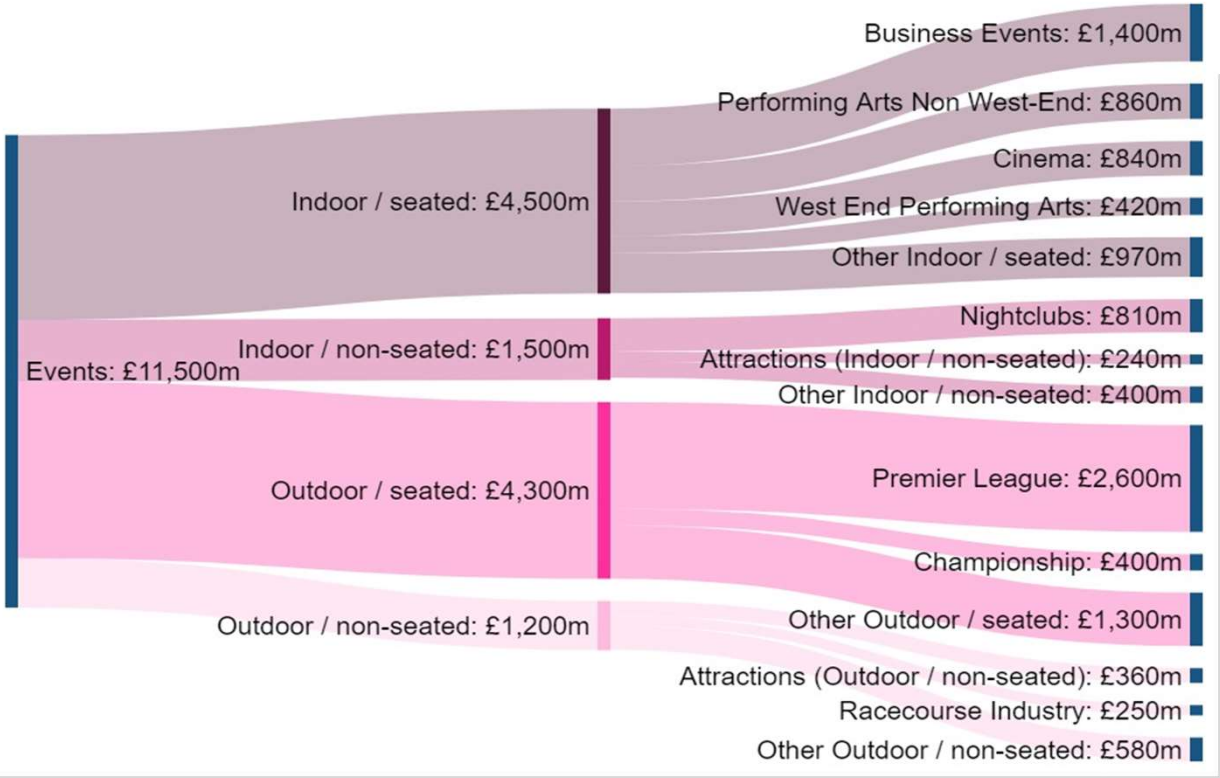
- Super-spreading events were seen as evidence of airborne transmission of SARS-CoV-2, especially in very poorly ventilated spaces
- 2020: After several months of debate: WHO, PHE and the CDC recognised that inhalation is likely the dominant transmission route in most settings
- Aerosols in exhaled breath, laden with virus particles, are important at close range ***and*** at longer distance.



The Events Research Programme was one of the four UK government's Roadmap Reviews for moving out of the pandemic



The economic impacts of live events



Events Research Programme Design

Focused on **settings, not sectors**, with a view to generating **generalisable evidence**.

- What is the impact on transmission? - **public health studies**
- Where are the risks? – **environmental studies**
- How do people behave? – **behavioural studies**
- What are the long-term economic and social impacts? – **socio-economic studies**

The Environmental Study - The Problem

Understanding **risks** relating to transmission at live events, especially airborne transmission and its relation to ventilation strategies

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)
- Low ventilation rates
- Large number of people present

…All these factors may be present at live events

Rationale for CO_2 monitoring: proxy for exhaled breath

- Airborne transmission, the known unknowns: Viral load, viral concentration in respiratory aerosols, aerosol concentration in indoor air, deposition rate, infectious dose… to name a few
- Airborne transmission – the known knowns:
  - CO_2 can be measured as a proxy for exhaled breath
  - Duration of exposure relates to risk of infection

Rationale for CO_2 monitoring: proxy for exhaled breath

- 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.
- The rate of removal is only dependent on the ventilation rate.

Rationale for CO_2 monitoring: proxy for exhaled breath

- CO_2 monitoring helps mitigate risks of airborne (aerosol) transmission by focusing on the **location**, and the **environment** created in the indoor spaces
- Exhaled breath might accumulate because of:
  - Poor ventilation for the space
  - High occupancy for the space (temporarily or consistently)
  - Or, more often, both
- Ventilation is an important mitigation measure to reduce risk of long-range airborne transmission

Our Approach

Focused on measuring simple parameters of Indoor Air Quality rapidly and at scale

- Understanding ventilation strategies and systems takes a long time
- Modelling airborne infection takes a very long time

→ Insights and results only applicable to the specific case studies examined in detail

- Measure CO_2 for exhaled breath and overall exposure
- Develop a classification system for venues
- Develop a set of Air Quality metrics, benchmarked against industry and government advice
- Monitor on a large scale and at high resolution
- **Be there, on the ground, at live events**
- Analyse air quality database for overall trends
- Analyse key types of spaces in depth to identify vulnerabilities
- Propose and test mitigations

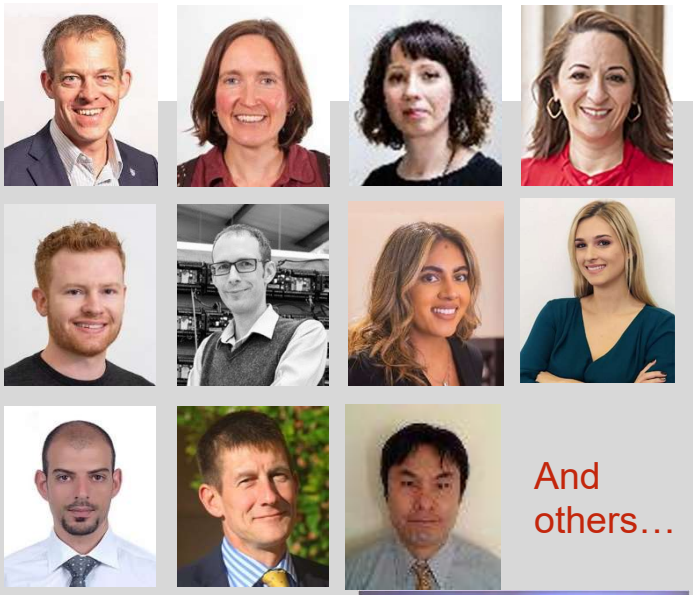
→ Results are more representative of the sector as a whole and give a fast indication of the scale of the problem

Getting Organised

Amassing an enthusiastic team from AIRBODS

- **Methods:**

- Air Quality measurement: CO_2, T, RH
- Database and dashboard setup
- Airflow measurements for validation of CFD simulations
- Basic analysis of ventilation systems
- Microbiological sampling of surfaces and air; PCRs for SARS-CoV-2
- Crowd observations, analysis of social grouping



And others…

Loughborough University UCL AIRBODS

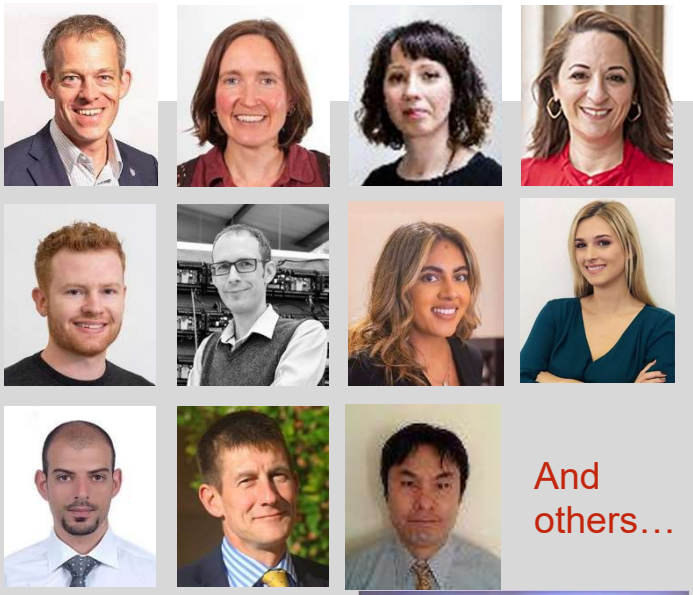
The University Of Sheffield. The University of Nottingham UKRI Engineering and Physical Sciences Research Council CIBSE

The real team at Wembley!

Getting Organised

Amassing an enthusiastic team from AIRBODS

- How many venues could we cope with?
- How many events could we attend in any given week?
- Getting legal agreements in place
- (UCL agreed to fund the study in the interim)
- Buying equipment at breakneck speed in the middle of a global pandemic
- Training and organising ~20 researchers
- Risk assessment, ethics approvals
- Online safety and social media advice



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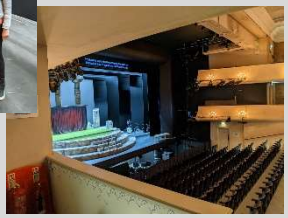
Getting Organised

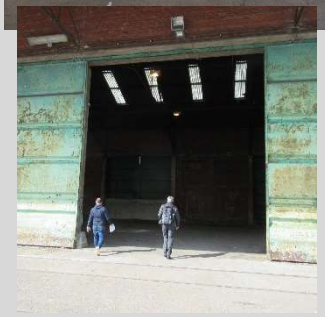
Learning on the fly: Initial site surveys, liaising with event organisers and venue managers, collecting data on event management, activities, timings and occupancy










Getting Organised

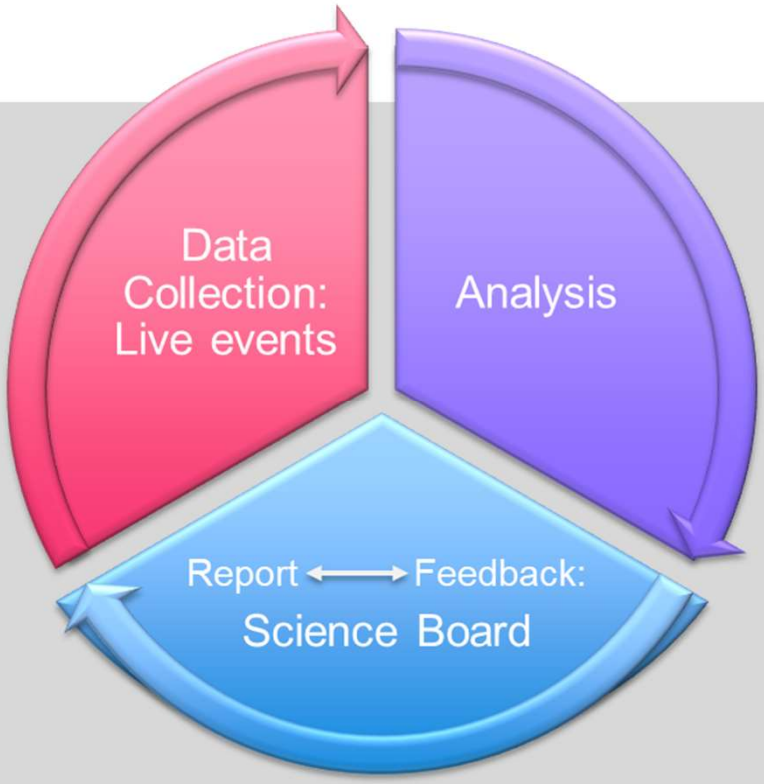
The installations – sensor installations and testing, setting up equipment around site, mapping out all the sensor locations, setting up an AQ dashboard to visualise data quickly, setting up a database

380 sensors were used, most transmitted their data to a central database every 2 minutes

The Process

The research programme was updated every week between April and August 2021

1. The research team attended live events to supervise the monitoring and understand how the events were run
2. Phase I: Data was quickly analysed for lessons learned
3. First reporting cycle to DCMS by May -> for ministerial review -> overall picture of AQ and analysis of exposure compared with “a day at the office”
4. Phases II-III of ERP planned and executed in rapid succession between April and May 2020
5. Weekly presentations and reports to Science Board
6. Phase III: Risks and mitigations communicated to Science board and venues – June-July 2020



The Process

The research programme was updated every week between April and August 2021

Data Collection: Live events

- 10 “outdoor” and indoor venues around the UK
- CO_2, Temperature and humidity were measured at high resolution by 385 NDIR sensors
- Between 50-75 monitors were deployed at each venue, distributed around as many indoor spaces as possible.
- Data transmitted to a dashboard every 2 minutes for real-time review online

Venue	ERP Phases	Number of Zones monitored	Total no of events monitored
ACC Good business	I	2	1
Circus Nightclub	I	4	2
O2 Arena	I	24	1
Crucible Theatre Snooker	I	16	11
Wembley	I, II, III	31	11
Royal Ascot	II	31	5
Download Festival	II	3	3
Piccadilly Theatre	III	28	3
Grange Festival	III	31	12
Leeds Playhouse	III	9	6

The Process

The research programme was updated every week between April and August 2021

- In total, 179 individual spaces were monitored over 55 events. An Air quality and crowd densities database was created.
- High resolution monitoring allowed us to develop a detailed understanding of the distribution of the air throughout larger auditorium spaces by the mechanical or natural ventilation systems
- Ventilation strategies and use of space varied widely across the venues.
- The majority of venues have a mix of different spaces with different uses within them.
- Even “outdoor” events will typically have indoor concession stands, bars and toilets. Marquees can become indoor spaces if they are unventilated.

Space classification criteria

Ventilation classification

- Outdoors
- Outdoors, sheltered
- Indoors, naturally ventilated, high ventilation
- Indoors, naturally ventilated, low ventilation
- Indoors, mechanically ventilated, high ventilation (ventilated to Covid guidance standard, eg CIBSE)
- Indoors, mechanically ventilated, low ventilation

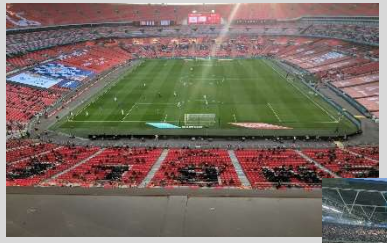
Use classification

- Arrival and Departure Areas
- Waiting Areas
- Concessions/ Bars – Standing
- Bars/Restaurants – Seated
- Spectator Areas
- Private Boxes / Meeting Rooms
- Toilets, Lifts, Stairwells (small, enclosed, short occupancy)

The Process

The research programme was updated every week between April and August 2021

- At science board every week, each research study presented their findings, leading to further collaboration
- We were able to link crowd densities with air quality, and to report on environmental conditions for the benefit of public health studies



Phase I, 18/4/21
FA cup semi-final
2,000 spectators

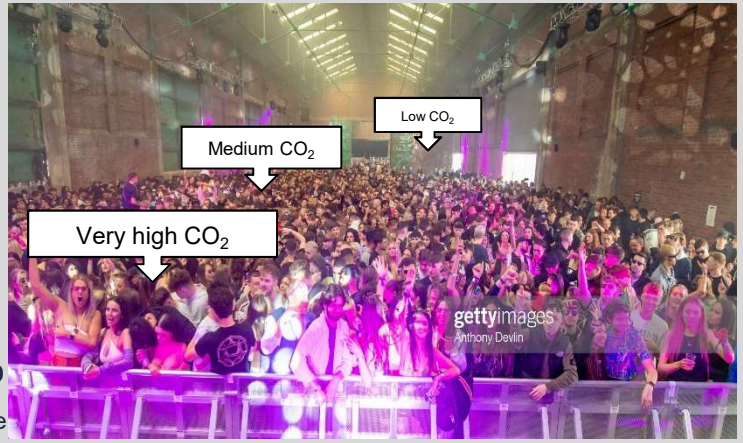
Wembley stadium

Phase II, 13/6/21, EUROs:
England vs Croatia,
22,500 spectators

Phase III, 7/7/21, EUROs semi final: England vs Denmark, ~70,000 spectators

Circus Nightclub

31/4/21, 3,000 people



Data Collection: Events Monitored

- Between the 17th April – 23rd July 2021, 90 events were monitored in total, spanning 13 types of events at 10 different sports, music and theatre venues
- High resolution monitoring of 179 individual spaces developed a detailed understanding of the distribution of the air throughout various spaces by mechanical or natural ventilation

Events	Venue	No. of events	No. of spaces
World Snooker Championships	Crucible Theatre, Sheffield	33	16
Emirates FA Cup Semi-Final	Wembley stadium, London	1	16
Carabao Cup Final	Wembley stadium, London	1	20
Good Business Festival	ACC Exhibition Centre, Liverpool	1	2
Circus Presents 'The First Dance'	Circus Nightclub (warehouse club), Liverpool	2	4
BRIT Awards	The O2, London	1	24
Emirates FA cup Final	Wembley stadium, London	1	26
EUROs 2020	Wembley Stadium, London	8	26 - 31
Royal Ascot Races	Royal Ascot Racecourse, Ascot	5	31
Download Festival Pilot	Castle Donington, Donington Park	3	3
Opera at The Grange Festival, Hampshire	The Grange, Northington	12	31
A Little Night Music	Leeds Playhouse Theatre and Opera North, Leeds	6	9
Comedy Nights	Piccadilly Theatre	3	28

Data Collection: Sensing and Monitoring

385 IAQ monitors, which measured CO_2 , Temperature and RH, were distributed around as many indoor spaces as practical at every venue

The CO_2 sensors were non-dispersive infrared (NDIR), capable of measuring within a range of 400–5000 ppm at an accuracy of ±30ppm (±3% of reading), with auto-calibration function

CO2 logger and desktop gateway

Monitored Zones Level 1

All zones marked in yellow

Zone	Description
A1	Gate J, opposite block 135
A2	Gate F, opposite block 110
A3	Seating block 137
A19	Female toilet, block 111
A20	Male toilet, block 109

Sensors were installed as appropriate to each venue; considering the geometry of the venue spaces, practical restrictions on wall fittings and discreet placement

Several loggers were placed in each space: on walls at a height of 2.3 m, and/or under auditoria seats, as relevant; and away from vents, doors or windows

Analysis: Space Classification

Ventilation Classification

- Outdoors
- Outdoors, sheltered
- Indoors, naturally ventilated, high ventilation
- Indoors, naturally ventilated, low ventilation
- Indoors, mechanically ventilated

Usage Classification

- Arrival and Departure Areas
- Dwelling Areas
- Concessions / Bars-Standing
- Bars / Restaurant-Seated
- Main Activity Areas (Structured)
- Main Activity Areas (Unstructured)
- Private Boxes / Meeting Rooms
- Toilets, Corridors, Lifts, Stairwells (small, enclosed, short occupancy)

Analysis: Air Quality Classification

Category	Expectation of indoor environmental quality	CO_2 above outdoors (ppm) assuming CO_2 emission of 20 l/hr/person	Total Indoor CO_2 values (ppm)
I	High	550	950
II	Medium	800	1200
III	Moderate	1350	1750
IV	Low	1350	1750

pre-pandemic…

Recommended targets for CO_2 levels for Indoor Air Quality, adapted from BSEN16798 , which states CO_2 values for ventilation related to occupant comfort

- For Covid mitigation, enhanced ventilation was recommended around the world, with different target CO_2 values recommended in different countries.
- In the UK, SAGE-EMG recommended prioritising spaces at above 1500 ppm first.

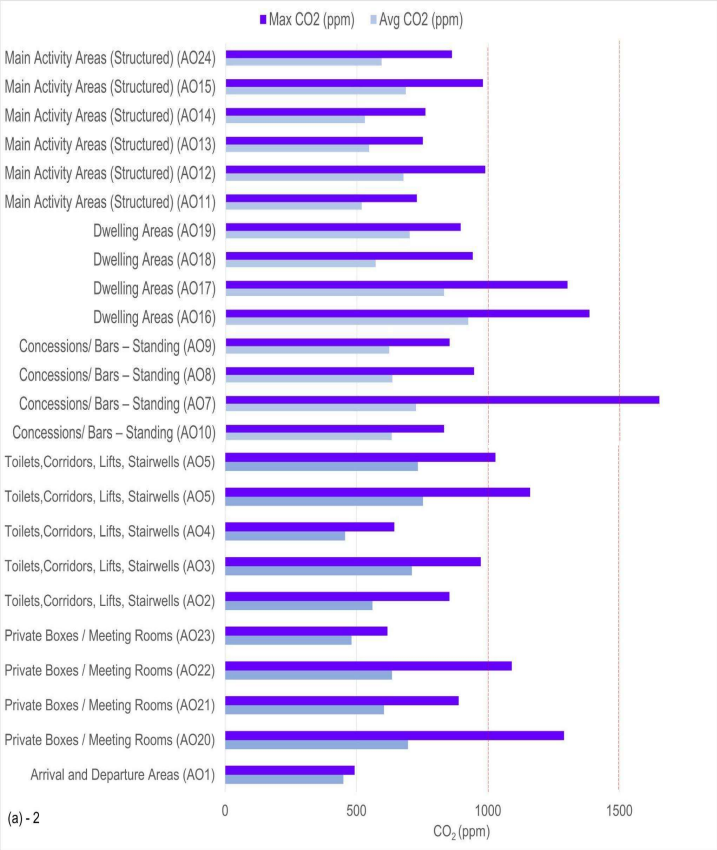
Analysis: Air Quality Classification

- For the ERP, we proposed a nuanced classification for IAQ based on seven bands of CO_2 concentrations
- All spaces were classified according to their air quality at every event using bands of A to G to allow a more nuanced assessment
- Air quality bands were calculated during events for the duration of an event, resulting in average and maximum bands

Air Quality Bands	Classification	Range of CO_2 concentrations - Absolute Values (ppm)	Range of excess CO_2 concentrations - Above outdoor (ppm)
At or marginally above outdoor levels	A	400 - 600	0 - 200
Target for enhanced aerosol generation (singing, aerobic activity)	B	600 - 800	200 - 400
High air quality design standards for offices	C	800 - 1000	400 - 600
Medium air quality	D	1000 - 1200	600 - 800
Design standards for most schools pre-Covid	E	1200 - 1500	800 - 1100
Priority for improvement (SAGE EMG)	F	1500 - 2000	1100 - 1600
Low ventilation/dense occupancy. Must be improved	G	>2000	>1600

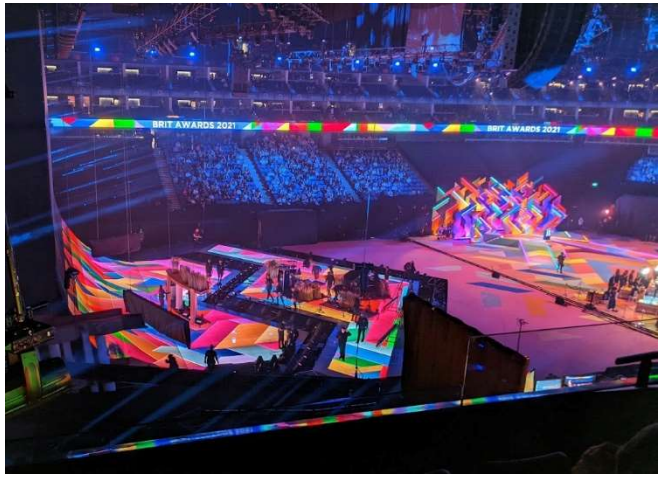
Key Research Outcomes

Results: Air quality distribution across different spaces in large venues, at 20% occupancy



Results from the O2 arena and Wembley Stadium events held mid-May 2021, with occupancy of about 20% venue capacity, demonstrate the variation of average and maximum CO_2 levels across a number of different spaces at the same event.

Large variability in CO_2 values throughout the venue, and with time



The 2020 Brit awards

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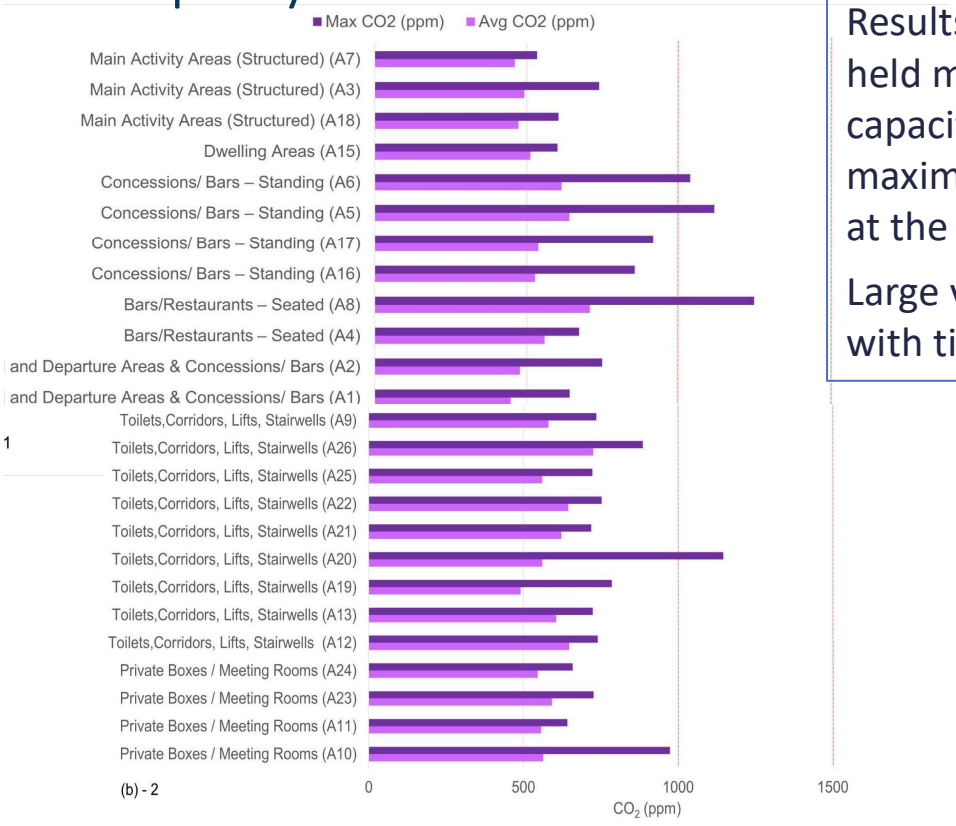

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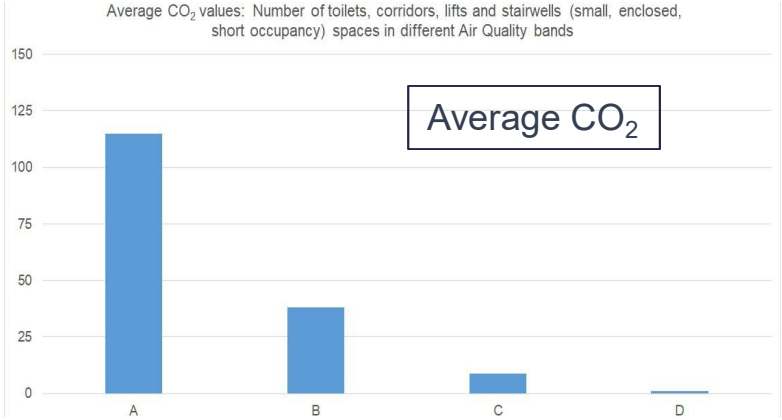
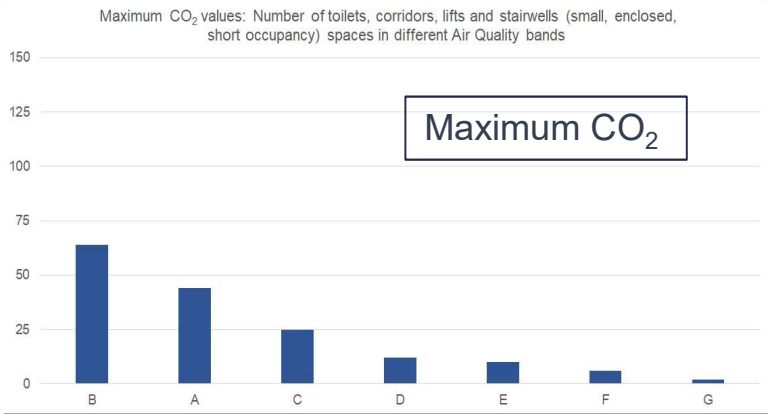
Large variability in CO_2 values throughout the venue, and with time

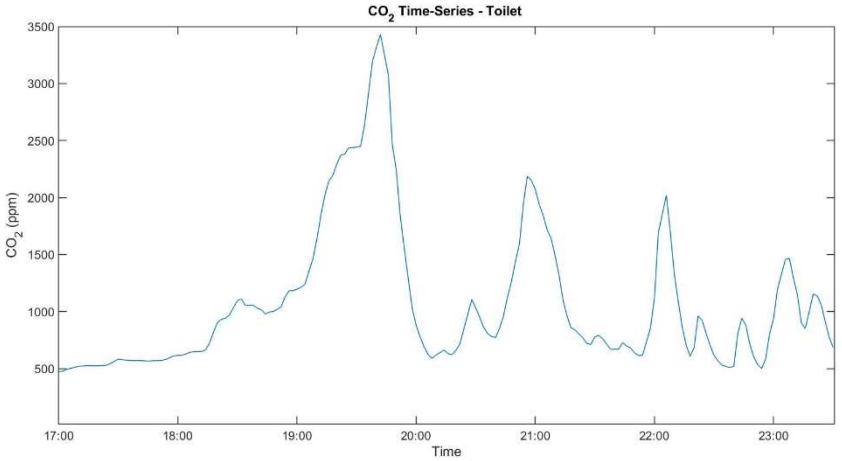
Wembley Stadium, FA cup

Types of spaces more prone to poor air quality



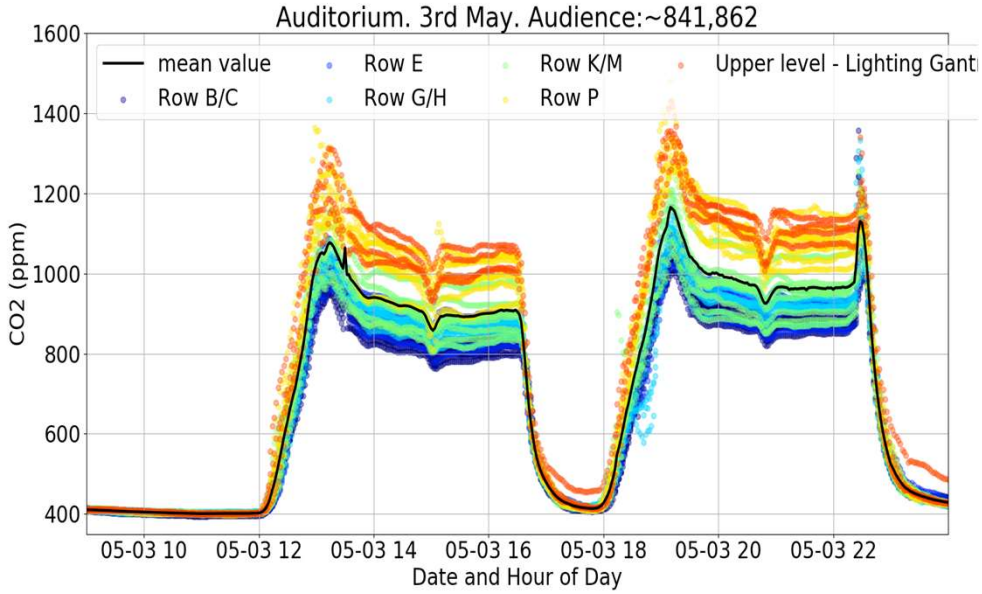


Toilets, corridors, lifts, stairwells (small, enclosed, short occupancy) were found to be poorly ventilated with very high peaks during busy times, at all ERP events.



CO_2 Time-Series in a single toilet at a high capacity event at Wembley Stadium, showing values up to 3500 ppm at times

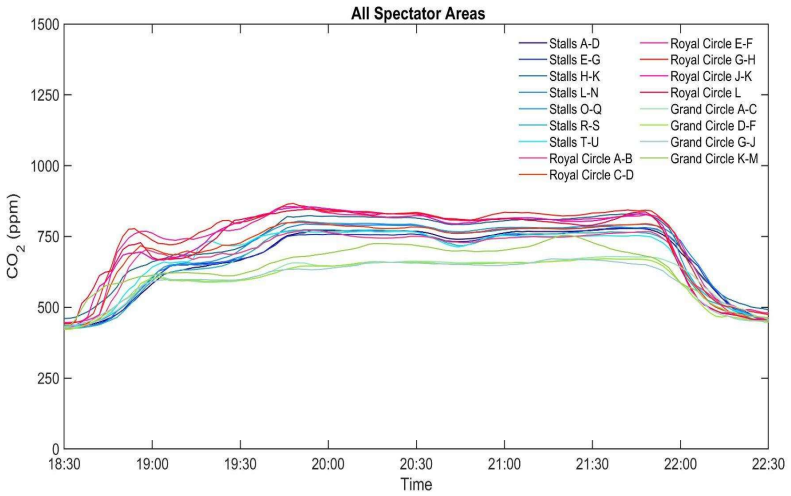
The Impact of ventilation strategy



Ventilation distribution at the Crucible Sheffield, a small theatre, as observed from 44 CO_2 monitors around the space

- The results demonstrate the space is not well mixed, with CO_2 values varying by nearly 400ppm from the back row to the front of the auditorium.
- The back row of the theatre peaks at nearly 1400ppm and stays above 1000ppm for the entire event.
- This variation in the space demonstrates the limitations of using CO_2 sensors only at the extract to control ventilation in a large space that may not be well mixed.

The Impact of ventilation strategy



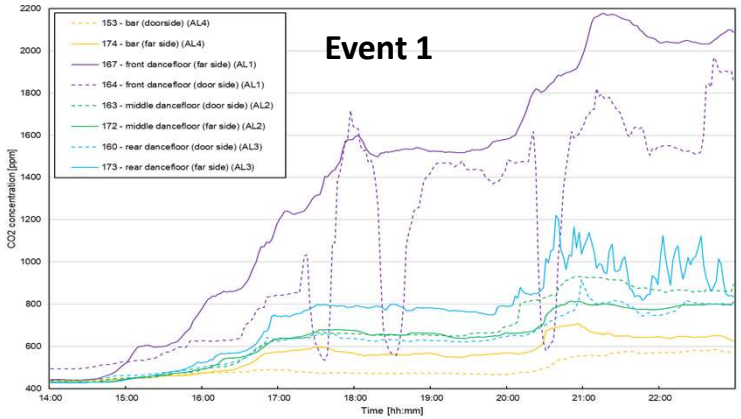
CO_2 data from 17 monitors distributed around The Piccadilly theatre, a large theatre with a high ceiling, on three different levels

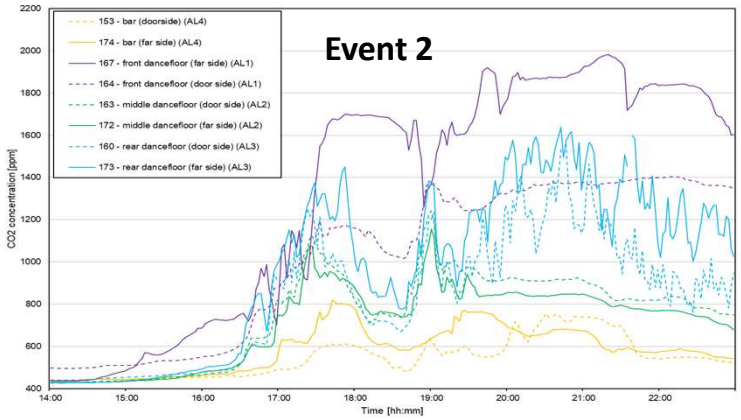
- Attendance was at ~50% of full capacity but the CO_2 data indicate a good ventilation strategy and a well-mixed space.
- The Grand Circle shows lower values than the other two auditorium levels.
- The values recorded never exceeded 800 ppm in all three spectator areas.
- The data shows constant levels of CO_2 indicating a continuous and sufficient fresh air ingress in the auditorium.

The Impact of Occupancy and ventilation distribution

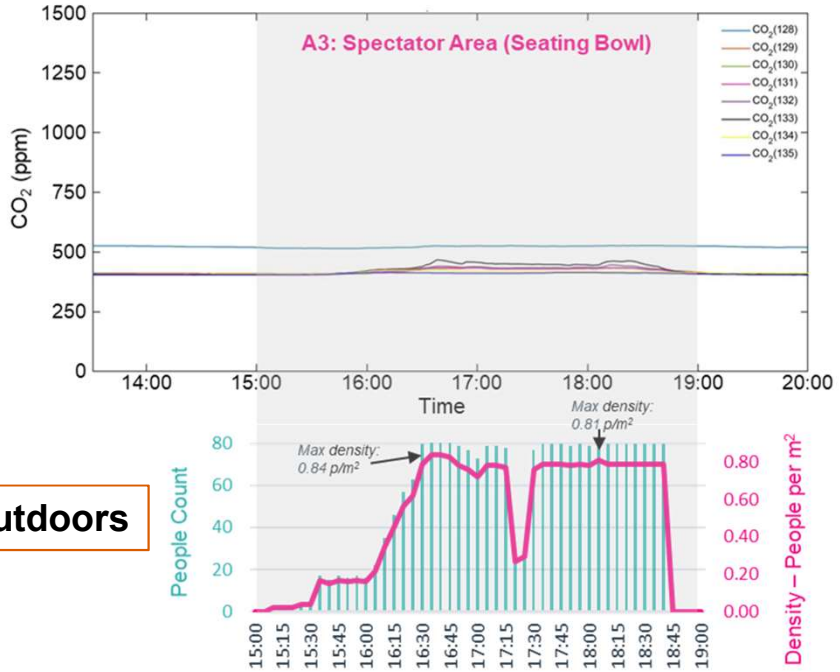
- Warehouse nightclub licenced for 10,000 people; pilot events were at 30% occupancy overall.
- Indoors, naturally ventilated, with very large openings on one side.
- By the bar end there was very high natural ventilation
- Openings were covered with butchers screen at the zone in front of the stage, blocking the ventilation, and peak CO_2 levels were above 2200 ppm.
- This was also the most densely occupied zone

Measured CO_2 concentrations from 33 sensors; plots show a subset of 2 sensors in each of four zones (colour-coded). Dashed lines denote a sensor on the side of the building that has door openings. Event ran from 2 to 11 PM.

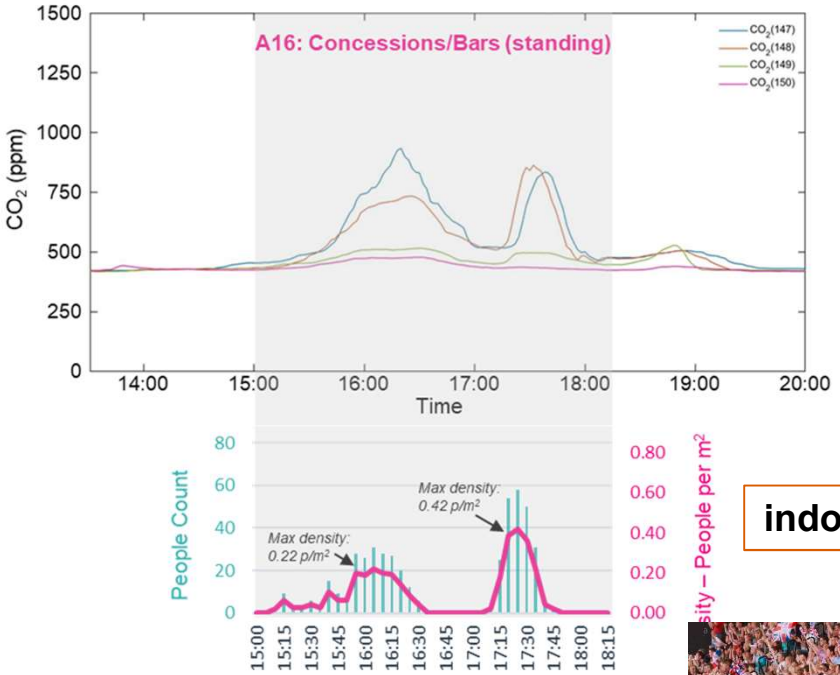




Links between air quality and crowding indoors, at low crowd density



outdoors



indoors

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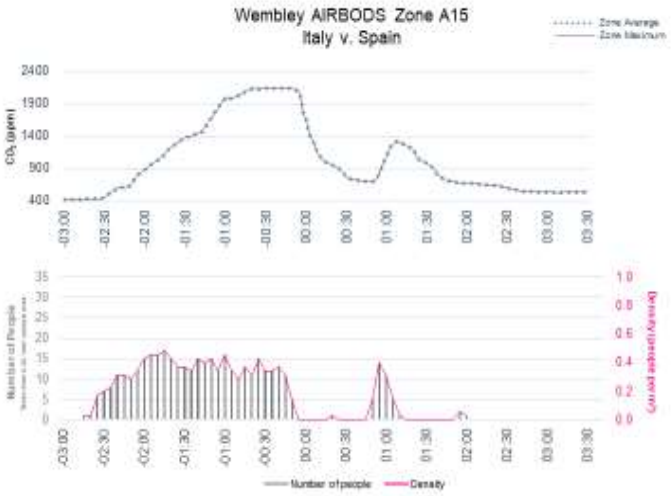
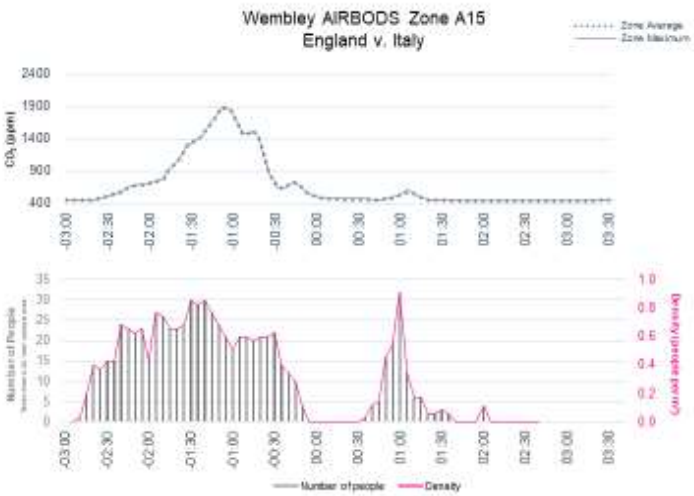
Findings for Air Quality and Mitigations

Quick mitigations can be achieved by identifying spaces needing improvement, and then opening windows or increasing ventilation systems, or by reducing crowding

Before mitigation



After mitigation



After opening additional vents: more people than before, yet better air quality

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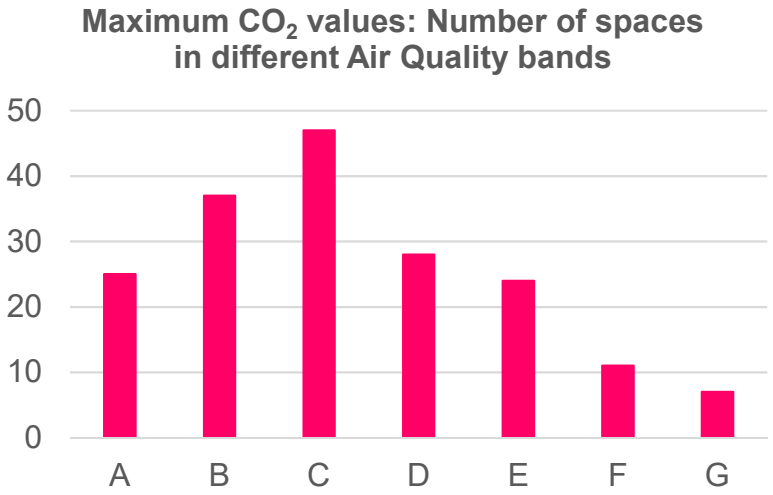
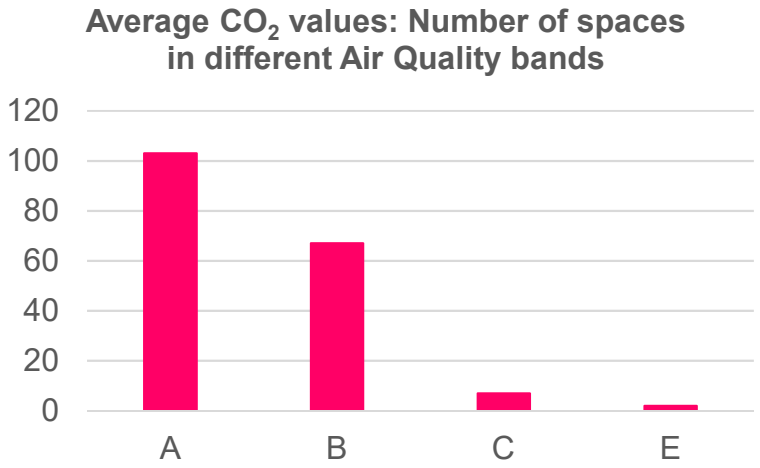
Air Quality across the board





Air Quality Bands	Classification
At or marginally above outdoor levels	A
Target for enhanced aerosol generation (singing, aerobic activity)	B
High air quality design standards for offices	C
Medium air quality	D
Design standards for most schools pre-Covid	E
Priority for improvement (SAGE EMG)	F
Low ventilation/dense occupancy. Must be improved	G

The number of spaces across the ten monitored venues, as aggregated by air quality bands for Average and Maximum CO_2 values. Data includes all venues and events from ERP Phases I, II and III.

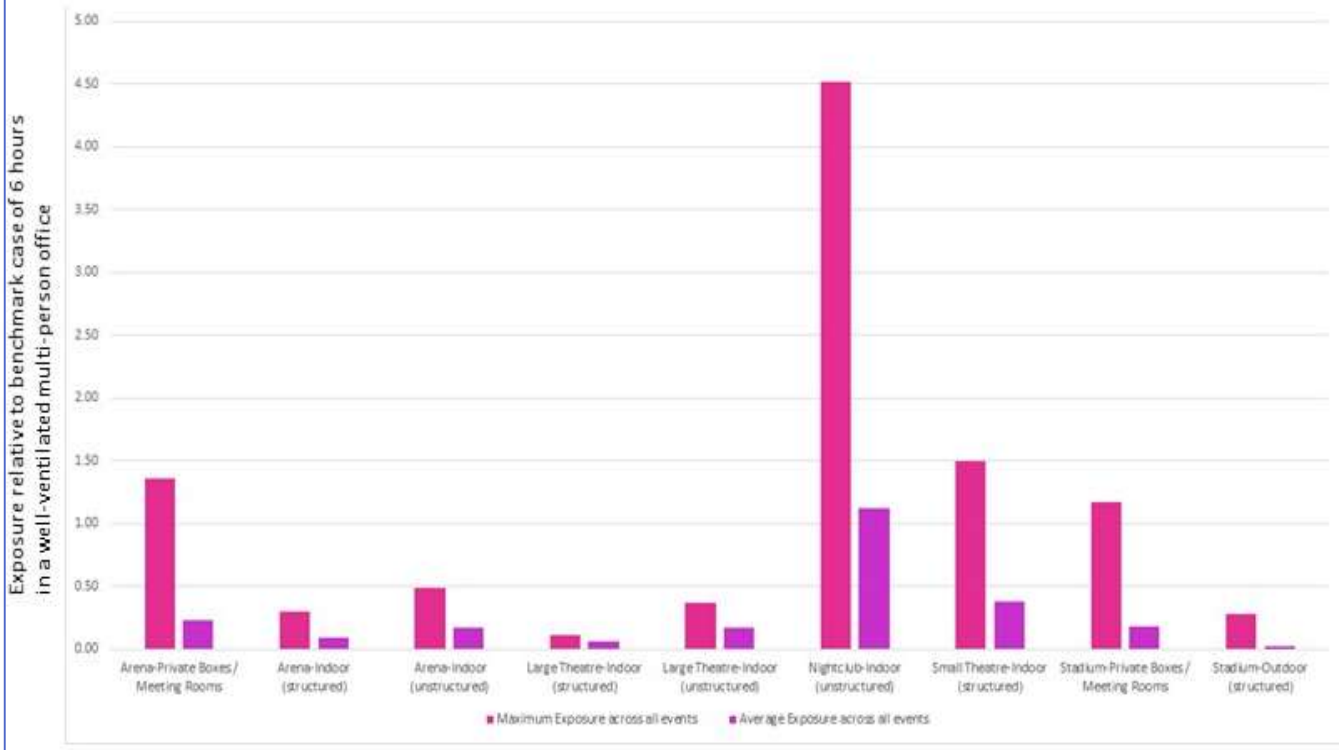
(Figures updated and reproduced following the published figures in Department for Digital, Culture, Media & Sport. Science Note - Emerging findings from studies of indicators of SARS-CoV-2 transmission risk at the Events Research Programme: environment, crowd densities and attendee behaviour)

Overall Findings for Air Quality

- SAGE EMG recommendations: improve spaces with CO_2 above 1500 ppm as a priority. 800 ppm: target for spaces with aerosol enhancing activities (singing, aerobic exercise, etc)
- At the 90 events monitored in 10 venues, the maximum recorded CO_2 values were below 1500 ppm in 161 of the spaces monitored. Where CO_2 levels were higher than 1500 ppm, this usually did not persist for longer than 1-2 hours.
- The average CO_2 levels during an entire event were below 800 ppm in 170 out of 179 monitored spaces
- In summary, Indoor Air Quality across the board was good or excellent

Duration of exposure and total personal exposure to exhaled breath

- In Phase I, we estimated customer exposure for each event and compared this with a benchmark case: a typical 6-hour day at the office
- These were estimated from average exposure and from maximum exposure, for the main activity area of each venue and each event on average
- Most activities showed lower “personal exposure” than the benchmark, but notably the nightclub was significantly more risky



Results from the ERP phase I

Findings and Recommendations for IAQ at events

- Poor IAQ with high CO_2 concentrations exceeding 1500 ppm, could be found in some 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
- High CO_2 values were found mainly where crowd density was very high but in some cases where the ventilation strategy was not well developed or where ventilation systems were faulty
- In some cases it was found that such a situation can persist for over an hour, potentially increasing the risk of transmission in those spaces if people spent much time there.

Overall Findings for Personal Exposure

- Mitigations were tested for such scenarios and found to be effective and often easy to implement
- A basic assessment of risk of exposure to exhaled breath demonstrated the risk is not higher than that of going to a large office, for the vast majority of the spaces observed
- ERP events were mostly held at below full capacity and when virus levels were very low in the community, and do not always reflect the situation for full capacity events. Some events reached almost full capacity during ERP and those presented higher risks.

Findings and Recommendations for IAQ at events

- There is less understanding in the community, of what ventilation is, and how it is achieved ***effectively***
- Large public spaces or venues cannot be assumed to be fully mixed and homogeneous in terms of air quality. If venues are monitored with only one or two CO_2 monitors, the measurements could lead to a significant overestimation or underestimation of the overall ventilation rates, and of the distribution of air quality.
- There are large variations in exposure to airborne diseases within a building and this can affect specific risk of transmission for people, depending on how long they spend in each type of space.
- 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.

Findings and Recommendations for Ventilation and IAQ

- Energy-saving has dominated the agenda for years, resulting in increasingly airtight indoor spaces where leakage from outdoors is minimised. Ventilation and air conditioning systems are normally set to recirculate stale air to improve thermal comfort and reduce energy costs, at the expense of fresh air.
- New approaches to CO_2 monitoring can be considered. It is inexpensive, can be deployed rapidly to identify areas where exhaled breath builds up in indoor spaces.
- Our research shows that useful lessons can be learned from a fast, *temporary* installation in real world conditions with high occupancy levels. Include high resolution monitoring, survey and understanding of the ventilation systems and in-person site surveys

Future Work: Integration

A lot of data was collected! This will be analysed further in subsequent research projects and used to inform modelling and experiments

These findings were instrumental to inform decision making

Our work contributed to enabling the re-opening of large, mass-participation events in the UK in June-July 2021, for the first time in over a year since the COVID-19 global pandemic in 2020, with nightclubs opening last.

AIRBODS

Future Work: Integration

Collaboration and integration between work packages of AIRBODS:

- Relative exposure index and proportion of people infected – implementation of the REI and PPI models on case studies of restaurants
- Building CFD models of case studies; for example of a theatre to understand ventilation effectiveness, thermal comfort and infection risks around the space and the links to exhaled breath

Publications

Conference Papers

Malki-Epshtein, L., Cook, M., Hathway, A., Adzic, F., Iddon, C., Roberts, B. M., Mustafa, M., (2022) Application of CO2 monitoring methods for post- occupancy evaluation of ventilation effectiveness to mitigate airborne disease transmission at events, CIBSE Technical Symposium, London, UK, April 2022

Journal Articles

Adzic, F., Roberts, B. M., Hathway, E. A., Matharu, R. K., Ciric, L., Wild, O., Cook, M., Malki-Epshtein, L., A post-occupancy study of ventilation effectiveness from high-resolution CO2 monitoring at live theatre events to mitigate airborne transmission of SARS-CoV-2 (Buildings and Environment, Covid special issue, June 2022)

Under Review

Burnside, G., et al, … Malki-Epshtein, L., Cook, M., Roberts, B. M., …et al COVID-19 risk-mitigation in reopening mass events: population-based observational study for the UK Events Research Programme in Liverpool City Region (submitted to The BMJ, September 2022)

Publications

In Preparation

- Monitoring and modelling the impact of ventilation on the far-field exposure risk to SARS-CoV-2 laden aerosols in restaurants (In final preparation for submission to Indoor Air)
- Evaluation of ventilation effectiveness to mitigate COVID transmission by rapid high resolution CO2 monitoring (In final preparation for submission to BSERT special issue)
- Ventilation assessment in semi-outdoor spaces during mass-gathering events to reduce the risk of airborne infection
- The impact of crowd densities and ventilation on air quality and risk of airborne transmission of Covid-19 in public spaces: an environmental study
- The potential impact of customer journeys through public event spaces on their exposure to Covid-19: a personal exposure study
- Holistic indoor environmental quality appraisal of a heritage theatre building under pandemic restrictions

Publications

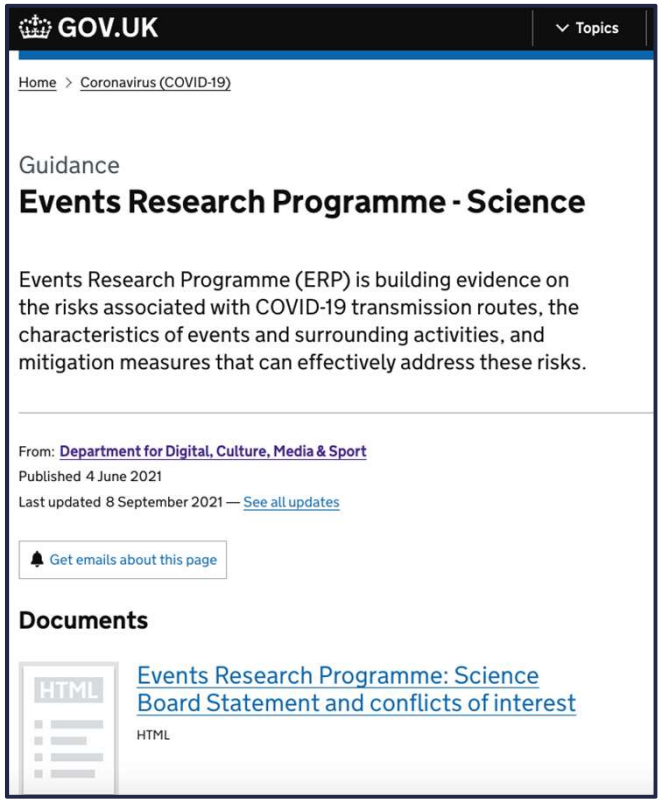
Reports

- **Findings from Phase I of the Events Research Programme** Events Research Programme - Phase I Findings (publishing.service.gov.uk)
- EMG-SPI-B: Application of CO_2 monitoring as an approach to managing ventilation to mitigate SARS-CoV-2 transmission
- **Findings from Phases II-III of the Events Research Programme** Science Note - Emerging findings from studies of indicators of SARS-CoV-2 transmission risk at the Events Research Programme: environment, crowd densities and attendee behaviour - GOV.UK (www.gov.uk)
- Events Research Programme Phase III: Development of Research Protocols - An environmental study on assessing and mitigating the risk of airborne transmission of SARS-CoV-2 at live events using CO2 measurement - GOV.UK (www.gov.uk)
- Events Research Programme Phase II: Protocol 3 - An environmental study on assessing the risk of airborne transmission of SARS-CoV-2 at live events using CO2 measurement
- AIRBODS WP3 Field Studies - Work Statement - GOV.UK (www.gov.uk)

Open Science – Gov.uk

- Open publication on gov.uk
  - Conflicts of interest
  - Research framework
  - Research protocols
  - Science Board statements
  - Data Dashboard

- If you wish to find out more, visit the Events Research Programme pages on gov.uk
  - Events Research Programme - Information page
  - Events Research Programme - Science page



Contacts and Sponsors

The AIRBODS project – to deliver guidance on the ventilation operation and future design of non-domestic buildings and to quantify the risk of, and reduce the transmission of SARS-CoV-2 in buildings, led by Prof Malcolm Cook, (AIRBODS Principal Investigator, Building Simulation lead)

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Today's speaker:

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