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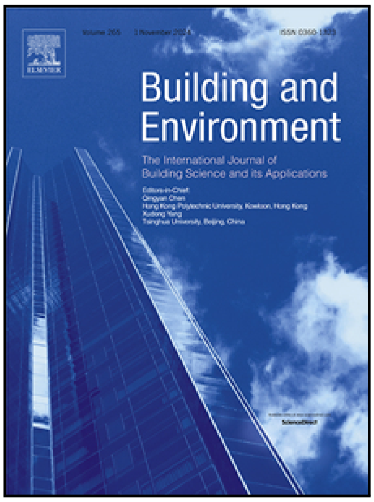

Air quality at mass gatherings: assessing ventilation and occupancy in marquees to evaluate airborne infection risk during the COVID-19 pandemic

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Highlights

- The largest monitoring campaign of marquees conducted worldwide.
- Acceptable air quality found in most venues investigated.
- Semi-outdoor events are not inherently low-risk to airborne transmission.
- Event intervals (breaks) and large ventilation openings improved air quality.
- Novel empirical evidence for future building regulations on semi-outdoor structures.

Air quality at mass gatherings: assessing ventilation and occupancy in marquees to evaluate airborne infection risk during the COVID-19 pandemic

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Abstract

The COVID-19 pandemic led to the cancellation of mass gathering events to slow the transmission of the SARS-CoV-2 virus, partially due to evidence that the virus can spread via airborne routes, especially in densely occupied, poorly ventilated spaces. Structures such as marquees (large tents), are commonly used at mass gathering events and were a frequently designated “outdoor safe space” during the COVID-19 pandemic. There is, however, scant evidence as to whether semi-outdoor buildings are sufficiently ventilated relative to the occupancy levels to reduce airborne transmission. As part of the largest study of mass gathering events to date, we measured ventilation and occupancy at 80 real events. We compared seven semi-outdoor spaces and one indoor space. Our results showed that most semi-outdoor buildings were sufficiently ventilated relative to the occupancy (mean CO_2 <800 ppm). Short peaks in CO_2 concentration of up to 1,200 ppm indicated intermittent, but brief, periods of insufficient ventilation relative to the occupancy in some spaces. High occupant density, heterogeneous occupant distribution (crowding), and poor ventilation management strategies negatively influenced the indoor air quality. Event management strategies, such as intervals between events, improved air quality. We conclude that semi-outdoor buildings are not inherently low-risk with respect to long-range airborne pathogen transmission and so require careful consideration for the ventilation provision relative to the occupancy. The evidence presented, using the largest field study of its kind worldwide, provides key evidence to inform revisions to building regulations and pandemic preparedness plans concerning the use of semi-outdoor buildings.

Keywords

Indoor air quality, airborne infection, ventilation, mass gathering events, SARS-CoV-2, COVID-19, post-occupancy evaluation.

1 Introduction

1.1 COVID-19 and restricting mass gathering events

Transmission of Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2), which caused the COVID-19 pandemic, led to 7.1 million deaths[1] worldwide by May 2025 [1] and widespread disruption to the global economy. Research published during the early stages of the pandemic indicated that mass gathering events could be focal points of driving localised outbreaks of the disease [2–11] because emerging evidence suggested that SARS-CoV-2 is transmitted by close contact airborne routes: exhaled virus-laden aerosol and droplets [12].

The proximity and duration people spend close to an infected individual increases the chance of infection [13,14]. Densely occupied spaces have higher airborne infection risk as occupants tend to crowd in certain areas at unstructured mass gathering events [15]. Activities common to mass gatherings such as shouting, singing, and aerobic activity are likely to increase the respiratory aerosol emission rate[2], and with it the risk of airborne transmission [16–22]. For these reasons mass gatherings or high-attendance events may be the foci of super-spreading events.

To reduce close contact between people and thus reduce the spread of SARS-CoV-2, many countries worldwide restricted culture, sport, and entertainment events in 2020 and 2021 [23]. Event closures were seen to be a vital non-pharmaceutical pandemic mitigation measure before vaccines became available [2]. Modelling studies have shown that limiting mass gatherings reduced transmission considerably [24].

[1] These are confirmed deaths. Actual deaths are predicted to be much higher at around 27 million [1].
[2] Although there is a high variation in viral load between infectors and therefore high heterogeneity in viable virus emission rates [70].

1.2 Economic impact of mass gathering event suspension

The suspension of mass gathering events is economically damaging. Live music events, for example, generated £1.1 billion for the UK economy in 2018, and the cost of lost ticket sales at arenas due to enforced COVID-19 closures was estimated as £235 million over a six-month period [25]. The economic and social damage of banning mass gathering and high-attendance events must be balanced with the benefits of reduced pathogen transmission, and evidence suggests events may be reopened with pre-event testing, close collaboration with local public health services, and with real-time monitoring of the indoor ventilation provision, usually via CO_2 measurement [26]. Risk of transmission cannot, however, be eliminated entirely [27].

1.3 Non-pharmaceutical interventions

Ventilation is a non-pharmaceutical intervention for reducing long-range transmission of airborne infections [13,14,16,17,28–33]. Other non-pharmaceutical interventions like pre-event testing, mask-wearing, reducing occupancy, and physical distancing all face implementation challenges such as low compliance, difficulty in enforcement, lack of acceptability, and economic unviability for mass gathering events [26,34–43]. Ventilating spaces with sufficient quantities of uncontaminated air is therefore one of the few infection risk reduction interventions that can be implemented without requiring occupant behavioural changes and so is a useful non-pharmaceutical intervention.

1.4 Ventilation in semi-outdoor buildings

The semi-outdoor temporary buildings described in this paper include marquees and large tents. They are alternatively called "temporary demountable fabric structures" elsewhere [44]. Semi-outdoor buildings are commonly used for outdoor entertainment purposes such as festivals, social events, and celebrations such as weddings. These structures, with or without operable side panels, provide shelter from wind, rain, or sun in otherwise primarily outdoor venues and events, or as supplementary spaces to indoor events. Being large, open spaces, usually without internal partitions, they can be used for a variety of functions as main event areas or as ancillary spaces. Semi-outdoor temporary buildings, therefore, represent a unique environment, which is neither fully indoor nor outdoor. The UK Health Act (2006), which pertains to smoking regulations, defines any building with a roof/ceiling as "enclosed" and buildings also with walls with gaps less than the total perimeter length as "substantially-enclosed" [45].

During the COVID-19 pandemic, semi-outdoor buildings were commonly recommended as "safe" places to hold mass gatherings or high-attendance events and were set up by pubs and restaurants to enable the hospitality industry to operate when indoor dining was banned [46]. For example, in England, they were allowed to be used to host wedding and funeral ceremonies when this was not permissible in fully indoor spaces [47], and the UK Government continued to encourage their use during the pandemic with the removal of planning permission requirements for semi-outdoor temporary buildings [48].

Despite their widespread use, there is currently very little evidence available as to whether semi-outdoor spaces are sufficiently ventilated to reduce occupant exposure to airborne pathogens. Existing industry guidance and British Standards on the operation of semi-outdoor spaces focus on public safety aspects such as structural strength, wind anchoring, fire and emergency exits, heating, and lighting [44,49]. Some limited guidance on how they should be ventilated was given via the Events Industry Forum which stated that event organisers should focus on improving ventilation by "fresh air or mechanical systems" and "removing side walls… of marquees [to] help circulate fresh air" [50]. Of the limited information which does exist, a controlled experiment in a semi-outdoor dining enclosure showed that closing all doors reduced the ventilation rate by

144-197% compared to having them open [51]. Clearly ventilation rates may be restricted in marquees, but the extent to which this affects indoor air quality at a variety of mass gathering events is unknown.

1.5 CO_2 concentration as a proxy for exhaled breath and airborne infection

Indoor air quality with respect to airborne infection risk is affected by several factors, including ventilation of uncontaminated air and the presence of different pollutant sources. A true measure of indoor air quality would contain information on the quantities of a variety of pollutants and pathogens likely to present in harmful quantities in the air. Sensing, especially in large studies, air quality measurements are commonly simplified and restricted to carbon dioxide (CO_2) concentration, as a proxy for indoor air quality and ventilation. CO_2 concentration measurements are a useful indicator of the amount of outdoor air ventilation relative to the occupancy [52].

CO_2 measured indoors above ambient concentrations (~430 ppm) are normally attributed to exhalation by people in the space, in the absence of other sources, such as combustion via a gas cooking hob. As a result, measuring CO_2 concentrations is an established proxy for exposure to exhaled breath[3], which may or may not contain pathogen-laden aerosols [15,53]. High CO_2 concentrations indicate either poor ventilation in the space, high occupancy relative to the space volume, or a combination of the two. CO_2 concentration gives an indication of the potential for long-range airborne transmission and can inform rapid assessment methods to identify environments at risk, e.g., Malki-Epshtein et al. [15], or sophisticated models, such as those of Jones et al. [14] and Iddon et al. [13], to make a detailed assessment of airborne transmission risk.

[3] Whilst the CO_2 concentration does not directly correlate with the concentration of any pathogen or pollutant present in the air, it does represent the accumulation of exhaled breath in the shared air [15].

1.6 The Events Research Programme (ERP)

The environmental study was part of the UK Government's Events Research Programme (ERP), which ran between April and July 2021 to assess the risk of reopening mass gathering and high-attendance events after COVID-19 pandemic closures and develop guidelines for the safer reopening of such events [54]. Its focus was on investigating how a range of non-pharmaceutical interventions, including ventilation, could reduce the spread of SARS-CoV-2 and is the largest such study to be conducted worldwide. The programme monitored a series of pilot events across 31 venues, including theatres [55], restaurants [56], nightclubs [15,26], sports stadia, and others [15,26,36,41,54,57,58]. The events were given special legal permission to run at a time when mass gathering events were otherwise illegal [59]. The participating venues were identified by the ERP programme to be representative of the events sector on a number of criteria, and participation for venues and attendees was voluntary. The ERP was designed and launched in an incredibly short time frame due to the ongoing public health emergency and so was limited in scope and thus could not measure infection risk or biological air quality markers explicitly. Nonetheless, it was the largest monitoring campaign of its kind worldwide and enabled rare access to study ventilation effectiveness through CO_2 measurements and link it to detailed occupancy distribution under real operational conditions of live events, at a large number of venues.

1.7 Study aim

The aim of this work is to provide evidence of the ventilation provision in semi-outdoor temporary buildings at mass gathering and high-attendance events. The ventilation relative to the occupancy of such venues is currently poorly understood and this paper fills a notable gap in the literature with the largest study of its kind undertaken worldwide.

In this study, the carbon dioxide (CO_2) concentration was measured at high spatiotemporal resolution in seven semi-outdoor marquees and one indoor space. Each space varied in terms of geometry, ventilation strategy, and function of use. The data were analysed to allow for a rapid air quality risk assessment to be made following the methodology described in [15,55]. Alongside the CO_2 measurements, the number of people in spaces was counted using video analysis or ticket scans to allow for comment on ventilation rates relative to the occupancy density and distribution. This study directly contributed to advice given to the UK Government on the risk of SARS-CoV-2 transmission if event businesses were allowed to reopen, and on how the venues can be operated safely to reduce risks of transmission [41,47,60,61]. A significant contribution to knowledge presented in this paper is new evidence to determine the suitability of semi-outdoor spaces for hosting mass gathering or high-attendance events and guidance on how they should be ventilated and operated to reduce the risk of long-range transmission of airborne infectious diseases.

2 Methods

2.1 Overview of methodology

The ERP programme included a large scale rapid environmental study to provide an evidence base of ventilation and air quality under real-world conditions during live events of varying levels of occupancy. A subset of venues from the ERP environmental study are studied and reported in this paper. This non-interventionist, observational monitoring study is centred around the measurement of CO_2 concentration inside the marquees and tents at several mass gathering events (Figure 1). The number of occupants in a space and their duration of occupancy was measured, as this is important for interpreting the CO_2 concentration data. Indoor temperature, relative humidity, and local weather were also measured as these influence thermal comfort. Thermal comfort may drive occupant behaviours, such as opening side flaps on the marquees to encourage ventilative cooling in hot weather, or increasing occupancy levels during rainfall, as people enter for shelter.

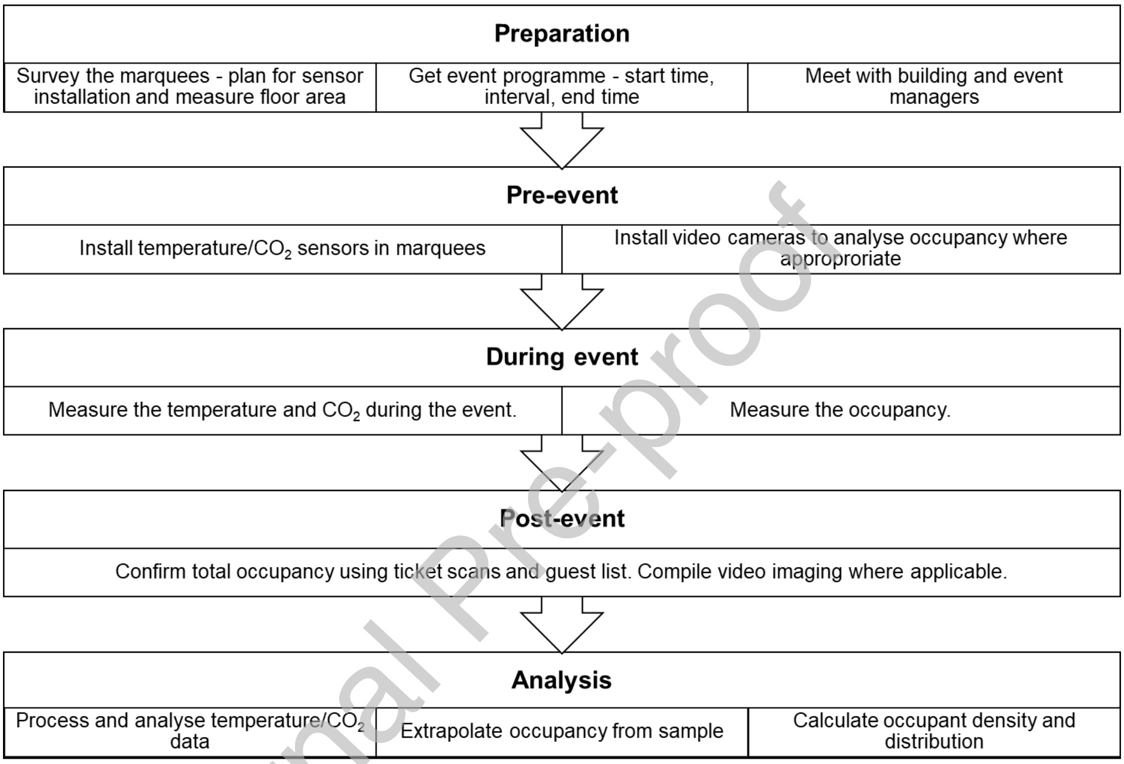


Figure 1: Diagrammatic overview of the field study methodology.

2.2 Events and venues

Four venues hosting 78 mass gathering or high-attendance events[4] in seven semi-outdoor buildings and two events at one indoor venue were monitored in England in 2021. The semi-outdoor events included horse racing, an opera festival, a rock music festival, and a

[4] An event is classed as, e.g., one graduation ceremony, one music set, or one theatre performance.

series of graduation ceremonies[5] (Table 1). The indoor event took place at a warehouse nightclub. Three of the monitored spaces (the graduation marquee, the music festival tent, and the nightclub) were the event's main activity areas. The five marquees at Ascot Racecourse and The Grange Theatre were ancillary areas (hospitality). The largest semi-outdoor space was the music festival marquee; the smallest was one of The Grange Theatre marquees (Table 1). All semi-outdoor spaces were constructed of an impermeable material to prevent rain ingress.

The definition of mass gathering events is given by one source as those with over 1,000 attendees [62]. Based on the number of event attendees, four venues were mass gatherings as they hosted over 1,000 people. The Grange Theatre and the graduation ceremony events were high-attendance events as there were less than 1,000 people attending.

[5] The graduation ceremonies were conducted outside of the Events Research Programme, but the data were monitored and analysed in the same manner as the ERP events. The venue was included in the study because it satisfied the conditions of a high-attendance event and the university was interested in conducting a live risk assessment during each ceremony to ensure they were operated within acceptable levels of risk with respect to transmission of airborne infection.

Table 1: Venue and event description, monitoring period, number of events, event attendance range, and marquee information.

Venue	Event	Type	Monitoring period (dd/mm/2021)	No. events with CO_2 monitoring	No. events with occupancy monitoring	Event attendance range	Attendance range (% of full capacity)	Building code	No. zones	Marquee function	Audience type	Ventilation type	Max. occupancy	Occupancy monitoring	Floor area (m^2)	Volume (m^3)
Ascot Racecourse	Horseracing (sports)	Semi-outdoor	15/06 to 19/06	5[a]	2	12,000	18%	RA1	1	Ancillary (Hospitality)	Structured seated	Mechanical	Varying (walk-in restaurant)	Video camera analysis	250	1,020
		Semi-outdoor			2			RA5	1	Ancillary (Hospitality)	Structured seated	Mechanical	271	Video camera analysis	1160	4,822
Donington Park	Music festival	Semi-outdoor	18/06 to 20/06	20[b]	1	10,000	11%	D	4	Main event (Dancefloor)	Unstructured standing	Natural	3,094	Video camera analysis	1911	10,000
The Grange Theatre	Opera festival	Semi-outdoor	02/07 to 24/07	12[a]	0	201 to 596	30-90%	GR27	1	Ancillary (Hospitality)	Structured seated	Natural	100	Guest list	255	638
		Semi-outdoor			0			GR28	1	Ancillary (Hospitality)	Structured seated	Natural	16	Guest list	25	63
		Semi-outdoor			0			GR29	1	Ancillary (Hospitality)	Structured seated	Natural	100	Guest list	255	638
Loughborough University	Graduation ceremonies	Semi-outdoor	19/07 to 29/07	41[b]	41	251 to 486	47-94%	LO	7	Main event (Ceremony)	Structured seated	Natural	499	Guest list	1500	11,550
Bramley Moore Dock Warehouse	Nightclub	Indoor	30/04 to 01/05	2	1	3,000	50%	NC	3	Main event (Dancefloor)	Unstructured standing	Natural	6,000[c]	Video camera analysis	1442[d]	17,000[d]

[a] One event per day.
[b] Each individual music set/graduation ceremony (separated by an interval) was counted as an event.
[c] The maximum licensed capacity was 10,000 but the usual capacity for events was 6,000 people.
[d] This is the area/volume of the dancefloor only which was used in the analyses (does not include the adjoining bar area).

(a) One of the two hospitality marquees at Ascot Racecourse (RA5 is shown).

(b) The marquee (circus tent) at the music festival (D).

(c) Hospitality marquees at The Grange Theatre (three were monitored, GR27, GR28, GR29).

(d) The marquee at the Loughborough University graduation ceremony (LO).

(e) The indoor nightclub event space (NC).

Figure 2: Photographs of the semi-outdoor and indoor spaces monitored.

At Ascot Racecourse, monitoring took place over five events on five separate days at the Royal Ascot horseraces (Table 1 and Figure 2a). The monitoring focused on two hospitality marquees that were used as restaurants. The marquees were sealed on all sides. Both marquees were mechanically ventilated and air-conditioned, with the ventilation rates adjusted depending on the weather and the amount of cooling required. Although the wider event was restricted to 18% of its usual attendance, the restaurants were occupied at their normal maximum capacity. Both marquees had “structured seating” with occupants sitting at tables. Dining tables in the RA1 Ascot marquee (Table 1) were booked by attendees for dining in three separate sittings daily throughout the afternoon and evening. Tables in the RA5 Ascot marquee (Table 1) were booked by attendees, who typically spent the majority of the 8 to 9 hour event inside the marquee, only briefly going outside to watch the horse races for 5 to 10 minutes at regular intervals. Occupancy was counted via table bookings.

Donington Park hosted Download Festival, a rock music festival, with monitoring over three days at 20 separate events (music sets) (Table 1, Figure 2b, and Appendix). The monitoring focused on one very large marquee (“big top” circus tent) that was used as a music stage and dance floor. The marquee was open on three sides and naturally ventilated. There was no mechanical ventilation, cooling, or adjustment of natural ventilation openings. Although the wider event was restricted to 11% of its usual attendance (10,000 people), there were no restrictions on the number of people who could occupy the marquee. The audience was free to move in, out, and around the marquee as they wished with unhindered access across the two-day music festival. Typically, the attendees moved to another area to watch another performance during intervals between acts (Table 3). Occupancy was counted using video camera images at 15-minute intervals across three zones within the main space (described in Section 2.5).

At The Grange Theatre, monitoring took place over 12 events on 12 separate days at an opera festival (Table 1 and Figure 2c). The monitoring focused on three hospitality marquees used as restaurants outside the main theatre during the 100-minute intervals between the main event. The marquees were sealed on three sides, with a fourth side that could be opened or closed depending on the weather. The marquees were naturally ventilated without mechanical ventilation or cooling. The wider event was restricted to between 30 and 90% of the usual attendance, but the marquees were fully booked and occupied. All three marquees had "structured seated" occupants sitting at tables. Occupancy was counted by table bookings.

At Loughborough University's graduation ceremonies, monitoring took place over 41 events (ceremonies) on 10 separate days (Table 1, Figure 2d, and Appendix). The monitoring focused on one marquee used to host the graduation ceremonies, with a stage and seating area for graduates and guests. The marquee was open on three sides at all times. It was entirely naturally ventilated without mechanical ventilation or cooling. The occupants were mostly seated and did not move around the marquee unless they were collecting their degrees. Access to the graduation marquee was restricted to the ceremony times, each lasting 45 minutes, followed by a 55-to-70-minute interval (Table 5, Appendix). Occupancy was counted and verified using event tickets.

The indoor nightclub is presented here for comparison purposes only and results are only presented in Section 3.5. The monitoring presented in this paper focuses on the dancefloor area of the venue at one event on a single day of the two event days that were monitored (Table 1, Appendix). The venue was a large (34,000 m^3) Victorian-era warehouse. Half of the space was the dancefloor, and the other half was a bar area. This research focuses on the dancefloor only, but previous work also considers the bar [15]. That was naturally ventilated on one side via six large warehouse door openings

(49 m^2). Ventilation through the three doors in the dancefloor area was restricted by metal shutters and hanging vertical plastic strip curtains to reduce noise egress from the venue, but enabled attendees to enter and exit the building reasonably freely.

2.3 Sensors to measure CO_2 concentration and indoor temperature

A high-resolution and rapid assessment methodology using CO_2 measurement was developed by the authors for the Events Research Programme[6]. This is reported, alongside the theoretical underpinnings of the method, in [15], and has recently been applied to theatre auditoria [55], a football stadium, a nightclub [15], toilets [57], and concession stands [58].

Measurement of indoor CO_2 concentration is a relatively cost-effective and convenient way to rapidly assess the ventilation provision relative to the occupancy. The method assumes that all CO_2 recorded above ambient concentrations (typically 430-450 ppm) is derived from human exhalation [15].

Calibrated non-dispersive infrared sensors (NDIR) measured CO_2 concentration and indoor temperature within each building, logging at two-minute intervals (Table 2). Most venues were monitored by Senseair Explora loggers. For the music festival tent, due to the risk of rain exposure, alternative NDIR sensors (HOBO MX1102A), which logged and stored data directly on the device, were used. Both sensor types were operated identically, and their data were analysed in the same way.

Multiple CO_2 sensors were distributed around each space to detect the spatial variation in CO_2 concentration and determine if the air in the space was well-mixed (see Appendix for marked floorplans with sensor locations). Such spatial variations might indicate

[6] The Loughborough graduation events were not part of the Events Research Programme, but the same monitoring and analysis methodology was applied.

uneven occupant distribution and/or poor ventilation effectiveness. The geometry and size of each venue dictated the number of sensors that were installed:

- At Ascot, 5 sensors were installed in each marquee RA1 and RA5
- At The Grange Theatre, 4 sensors were installed in marquee GR27, 1 in GR28, and 4 in G29
- At the music festival (D), 19 sensors were installed
- At the graduation ceremony marquee (LO), 23 sensors were installed
- Finally, at the only indoor event reported here, 33 sensors were installed in the nightclub (NC).

Most sensors were installed on supporting columns at a height of 2.3 m from the floor. Floorplans with sensor positions are given for some venues in the Appendix. Sensors were usually hung around the internal perimeter of the marquee, but there were four central supporting columns in the music festival tent to which sensors were affixed and to a crowd barrier in front of the stage. Sensors were additionally installed under seats in the graduation marquee and on speakers at a height of 5.8 m from the floor in the music festival tent.

Care was taken to avoid placing sensors next to ventilation inlets or outlets, and any potential irregularities in the recorded data were investigated during the analyses. For example, the perimeter sensors at the music festival were ultimately damaged by rain and these data were discarded. Installation of multiple sensors within marquees resulted in some marquees being divided into several monitoring zones for analysis, depending on the size.

Table 2: Sensor types, logging intervals, and accuracy

Data storage	Logging interval (mins)	CO_2 (ppm)		Temperature (°C)		Calibration by
		Accuracy (±)	Range	Accuracy (±)	Range	
LoRaWAN connection to 4G hub and data stored on a remote cloud server	2	30 (or 3%)	400 to 5000	0.2	-20 to +60	Manufacturer and routine auto-calibration
Logged to device	2	50 (or 5%)	0 to 5000	0.21	0 to 50	Research team

2.4 Air quality classification

From a public health perspective, it is useful to understand the overall ventilation performance of the range of semi-outdoor and indoor buildings at these types of mass gathering events. An air quality classification[7] based on bands of CO_2 concentrations (as a proxy for exhaled breath) was applied to measurements taken at the events. Full description and justification of the air quality bands is provided in [15]. To determine overall air quality based on the classifications (Table 3), CO_2 from all sensors placed in each individual space (zone) were averaged over time, resulting in a spatiotemporal average of CO_2 concentrations. Only the occupied times were considered in the averaging time, based on to observed occupancy scenarios. Furthermore, the point-in-time maximum CO_2 concentration was identified for each zone from the measured data for each event.

[7] Classifying each space based on the measured CO_2 concentration is a useful metric for indicating the ventilation provision relative to the occupancy levels. It does not, however, directly correlate with risk of airborne infection but it does represent the accumulation of exhaled breath in the shared air.

Table 3: Air quality classifications and bands [15]**.**

Air Quality Classification	**Band**	**Range of absolute CO_2 concentrations (ppm)**
At or marginally above outdoor levels	A	400-600
Target for enhanced aerosol generation (singing, aerobic activity)	B	600-800
Typical air quality design standards for offices	C	800-1000
Medium air quality	D	1000-1200
Design standard upper limits for most schools pre-COVID-19	E	1200-1500
Priority for improvement (SAGE EMG)	F	1500-2000
Low ventilation/dense occupancy. Must be prioritised for improvement	G	>2000

2.5 Measurement of occupancy and occupant density

Occupant density (number of people per unit of floor area, people/m^2) was measured and calculated to understand how people moved in, out, and around each event venue over time. Occupancy was measured in two ways during the live events. Video cameras were installed to analyse the movement and behaviour of attendees at two venues: the semi-outdoor music festival and the indoor nightclub [63]. In all other venues, occupancy was determined from ticket sales and guest lists.

Occupant density is important in this context because when paired with the corresponding CO_2 concentration measurement it can aid understanding of whether ventilation is sufficient relative to the occupancy. A range of occupant densities may be expected at the different mass gathering events that were monitored, which can vary due to movement parameters (e.g., speed and flow) and movement type (e.g., queuing or general movement) [64]. Densities of 0.3 to 2.2 people/m^2 might be expected where people are walking on flat ground or 0.8 to 5.3 people/m^2 in a queuing or waiting area [64]. At occupant densities of 2 people/m^2, the occupants may still move around freely, but at 4-5 people/m^2 movement is restricted [65]. Occupant densities above 5 people/m^2 in a stationary crowd are unlikely to occur as this represents the upper limit for occupant comfort [65].

2.5.1 Counting occupants using video cameras

At the music festival and nightclub, cameras recorded video imagery of the audience inside and immediately outside around the buildings during the entire event period (see Gwynne et al. [63]). The method has been successfully applied at other mass gathering events [66,67]. Three video cameras each were located in the music festival tent and three in the indoor nightclub (dancefloor area only). The cameras were pointed such that each covered a different zone: front, middle, and back (Figure 16 in Appendix). These zones were selected based on the assumption that audience densities were likely to differ based on proximity to the stage. The zones were delineated by splitting the dancefloor areas into thirds. Selection of these areas was based on the ability to capture a sufficiently large area within the view of the camera (>25 m^2), distance to the camera (the closer the better whilst still fully captured by the camera), lighting levels (higher the better), physical landmarks (enabling floor measurements to be more reliable and then superimposed on the crowd densities), and the presence of representative crowd densities to maximise accuracy of counts (e.g., not on the periphery where densities were affected by arrivals, etc.).

Researchers then reviewed the video imagery and manually counted the number of people in each zone at 15-minute intervals at the music festival and 5-minute intervals at the nightclub. People were defined as being inside an area if their shoulders were inside the overlay section (Figure 3) because, depending on the crowding level, it was not always possible to see the feet of those attending. Although the perspective of the cameras may have affected the precision of this count, the proximity of the cameras to the zones and that they were static meant that the impact was consistent throughout. Counts were undertaken on video imagery on 19 June (11:00-20:00) at the music festival and on 1 May (16:00-20:00) at the nightclub because ticket scan data indicated these days had the highest number of attendees onsite.

Occupant density (people per area) was calculated from the occupant counts. Estimates of occupancy per zone were calculated using the head count per zone and the area of the usable floor space within each count zone on the assumption that the occupancy counts in three areas can be applied to the remaining useable area within each zone.

Figure 3: Video camera image and overlay section (measurement area) at the indoor nightclub. The same method was used at the semi-outdoor music festival.

2.5.2 Counting occupants using ticket sales

At the remaining event venues, occupants were counted using ticket scans. This resulted in occupancy data that were coarser with respect to both spatial and temporal counts. At the Ascot RA1 marquee, occupancy was known for three separate restaurant meal sittings via table bookings. At the Ascot RA5 marquee, occupancy was known for a single 8-9 hour period. At the graduation ceremony occupancy was known via ticket scans upon entry at the start of each 45-minute ceremony. The occupancy of the hospitality marquees at The Grange Theatre was known via guest list records. Precisely how and when people moved around these venues was less well known than at those with dedicated video cameras installed for detailed analysis. The best information came from the graduation ceremony where it was observed that most occupants were seated throughout, except when collecting their degrees. At the Ascot RA5 marquee, occupants were observed to briefly leave for 10-15 minutes to watch a race (each race was three minutes long), but precisely when they did so, and in what number, was unknown. As such, the majority of the analysis concerning occupancy density focuses on those events when it was well known: the music festival, the nightclub, and the graduation marquee.

3 Results

To assess air quality at the mass gathering events, firstly, the spatiotemporal averages and maximum CO_2 concentrations were analysed for each semi-outdoor space across all events (Section 3.1), following the method described in Section 2.4. The data were also examined by individual space to determine whether any specific areas were prone to poor ventilation. Secondly, cases of poor ventilation were further investigated in relation to weather conditions and occupant behaviour (Section 3.2). Thirdly, how the spatial distribution of occupants within a space affects CO_2 concentration was examined (Section 3.3). Fourthly, the relationship between CO_2 concentrations and similar occupancy densities across different venues was explored (Section 3.4). Finally, a comparison was made between semi-outdoor and indoor spaces (music festival vs. a nightclub) (Section 3.5).

3.1 Overall air quality for all semi-outdoor events monitored

An air quality assessment was conducted for each of the seven spaces throughout 78 events to rapidly evaluate the overall air quality at semi-outdoor events for the purpose of public health advice in the context of the Events Research Programme. This was done by calculating the average and maximum CO_2 concentrations and assigning them to a band as defined in Table 3. For each space, an average of all sensors in the space was taken over the entire occupied period of the event (i.e., the spatiotemporal mean). The maximum CO_2 concentration represents the highest concentration recorded in a space over the occupied period (i.e., the single point-in-space and point-in-time maximum).

Across all semi-outdoor events, the mean average CO_2 concentration in seven venues was in Band A or B, indicating the mean air quality was close to outdoor air quality in 100% of spaces (Figure 4). The maximum CO_2 concentration showed that the ventilation provision was better than the ventilation standards for offices, with 96% of spaces falling into Bands A to C.

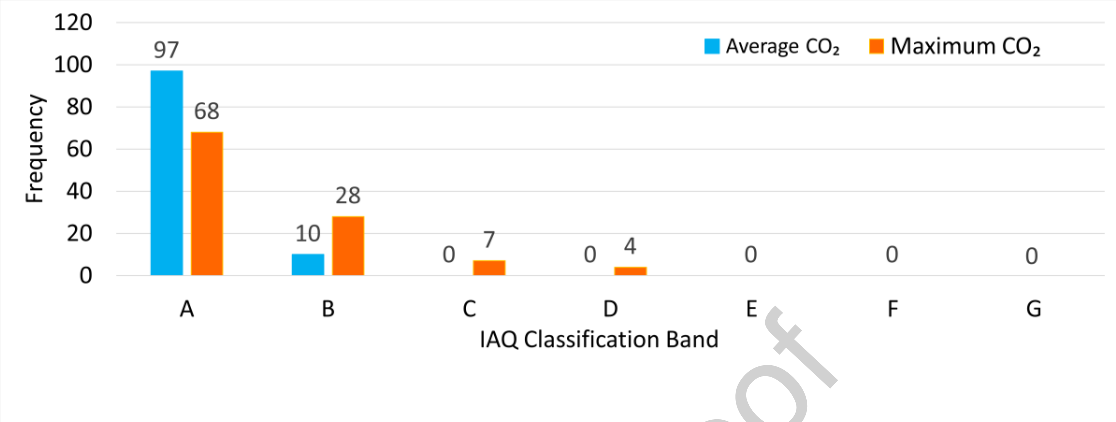


Figure 4: Spatiotemporal mean average and maximum CO_2 in all semi-outdoor spaces monitored over all events, aggregated by air quality bands.

To identify if any of the monitored spaces were prone to episodes of poor air quality that might require intervention, and to identify potential ventilation design interventions, the maximum CO_2 concentrations and the means of all spatiotemporal averages and were calculated for each marquee over all the events (Figure 5).

The means over all events showed that the average CO_2 did not exceed 600 ppm which placed majority of spaces in IAQ band A. Only hospitality marquee RA5 had a mean of 681 ppm over 5 event days, and was classified in IAQ Band B.

Looking at the maximum CO_2 for each space over the all the events, hospitality marquees RA1 and GR27, as well as the graduation marquee LO were classified into IAQ Band B. Hospitality marquee GR29 fell into Band C for maximum CO_2, indicating “typical air quality design standards for offices”. Finally, hospitality marquees RA5, GR28 and the music festival marquee were all placed in IAQ Band D, which indicates “medium air quality” (1000-1200 ppm) (Figure 5). The highest maximum CO_2 concentration was recorded in a mechanically ventilated, closed-sided hospitality marquee (RA5, 1151 ppm) on the coldest day. Hence, the effect of outdoor weather on indoor air quality was further investigated in Section 3.2.

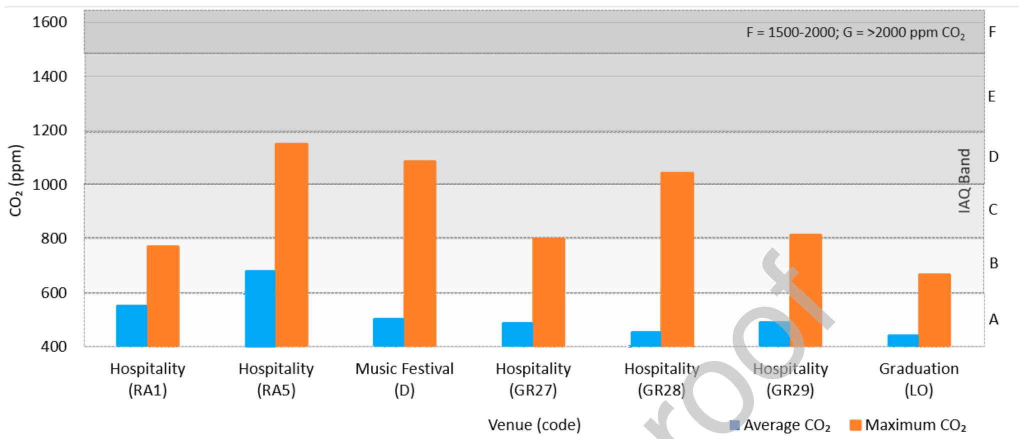


Figure 5: Spatiotemporal mean and maximum air quality classification bands for semi-outdoor spaces across all 78 events.

3.2 Effect of weather on attendee behaviour and performance of natural and mechanical ventilation

This study identified that changes in occupant behaviour and ventilation practices in response to variations in weather at mass gathering events can result in changes to indoor air quality.

3.2.1 Inclement weather (rain)

Events during rainy weather may encourage semi-outdoor buildings to be operated or occupied differently than in dry weather. To demonstrate the impact of this, event days with and without rain were compared. This comparison is shown in Figure 6 via a time series of spatially averaged CO_2 concentration over time in three naturally ventilated marquees (GR27, GR28, GR29) when they operated during events on two different days: a day with cool temperatures and high rainfall[8] and a warm dry day without rain. The three marquees had similar occupation profiles on both days[9].

The CO_2 concentrations in three hospitality marquees were 42 to 83% higher on the rainy day than on the dry day (rainy day maximum was >1000 ppm in GR28 and >800 ppm in GR27 and GR29 vs. dry day maximum <500 ppm).

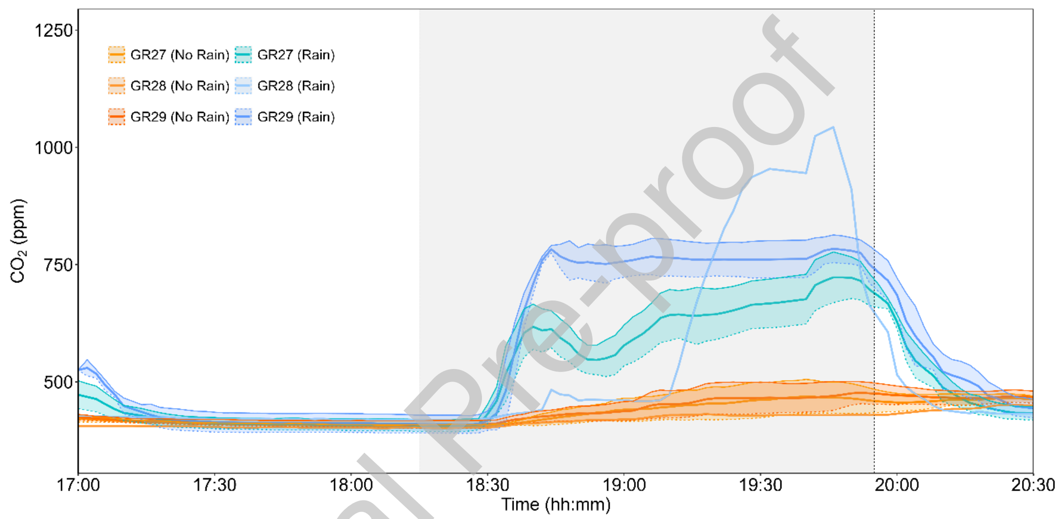


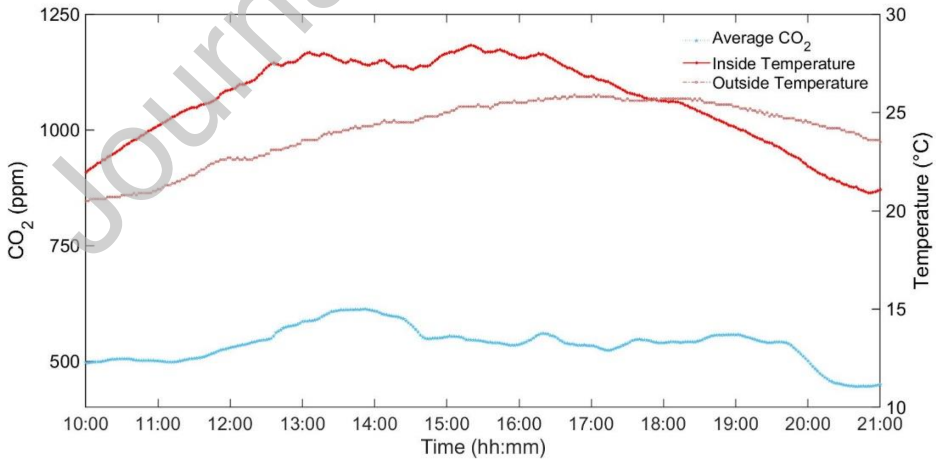
Figure 6: Spatially averaged CO_2 over time in three naturally ventilated marquees (GR27, GR28, GR29) on a day with and without rain. Solid lines indicate the spatial average for each zone, with the shading indicating the minimum and maximum values, where there was more than one sensor in the space. The shaded section shows occupied time from 18:15 to 19:50.

[8] Mean outdoor dry bulb temperature during the rainy day event was 17°C, compared to a mean outdoor temperature of 29°C on the dry day.
[9] Tickets sales for the main theatre event were similar, and the event duration and management were similar, but the precise occupancy on the individual hospitality marquees was not monitored.

3.2.2 Impact of mechanical ventilation at high outdoor temperatures

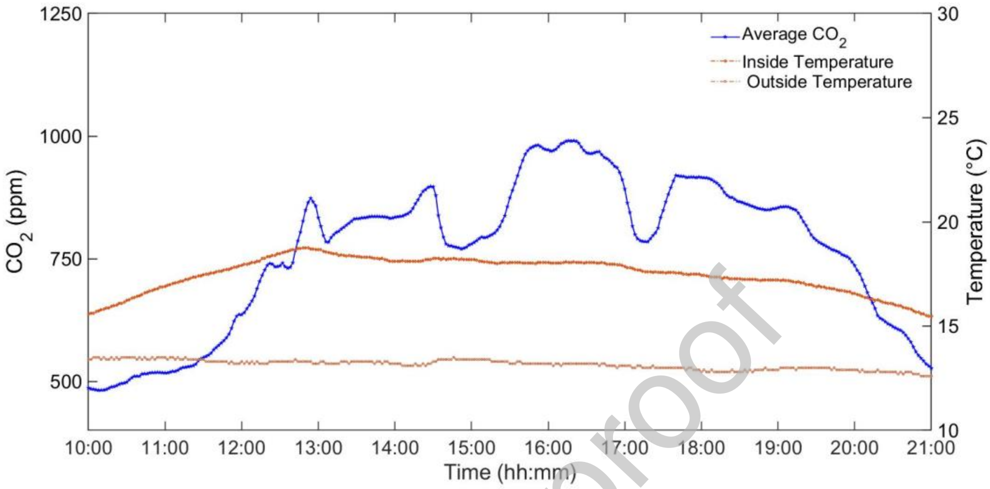
Just as rain may alter how semi-outdoor spaces are operated and occupied, on very hot days, operable windows and doors may be opened, and if present, mechanical ventilation system flow rates increase. A time series of spatially averaged CO_2 concentration in a mechanically ventilated and air-conditioned hospitality marquee (RA5) is presented alongside indoor and outdoor temperature on a hot and cold outdoor day (Figure 7a and Figure 7b).

The CO_2 concentration was lower on a day with a higher outdoor temperature (cf. Figure 7a and Figure 7b). For example, on a day with a mean outdoor temperature (during the occupied period[10]) of 25.4°C, the mean indoor CO_2 concentration was 550 ppm (maximum 600 ppm). Conversely, on a day when the mean outdoor temperature (during the occupied period) was much cooler (13.7°C), the mean indoor CO_2 concentration was higher at 814 ppm (maximum 1000 ppm) at similar occupancy. This is discussed further in Section 4.1.2.



[10] Between 09:00 and 21:00.

(a)



(b)

Figure 7: Outdoor temperature, indoor temperature, and spatially averaged indoor CO_2 concentration over time in a mechanically ventilated marquee (RA5) on (a) a hot weather day and (b) a cool weather day.

3.3 The effect of high ventilation rates in open-sided marquees with high and low occupancy

Although ventilation rates were not measured directly, the data indicate that there was sufficient ventilation relative to the occupancy in most marquees at most events (Figure 4 and Figure 5 in Section 3.1). The investigation of the relationship between occupancy and CO_2 concentration further evidences this. Two marquees, both with open sides for ventilation, are compared. One has low occupant density and a seated audience (Section 3.3.1), the other high occupant density and a standing unstructured audience (Section 3.3.2).

3.3.1 Low occupancy marquee

To demonstrate how CO_2 concentration changes with occupancy in a low-occupancy marquees, a scatterplot of occupancy as a percentage of total occupancy against the indoor spatiotemporal average, mean, and maximum CO_2 concentration measured in the graduation marquee over 41 events (Figure 8). In this case, the CO_2 concentrations remained similar at occupancy levels ranging from 47 to 94% of maximum capacity. There was no observed trend of increasing CO_2 concentration with increasing occupancy at these occupancy levels.

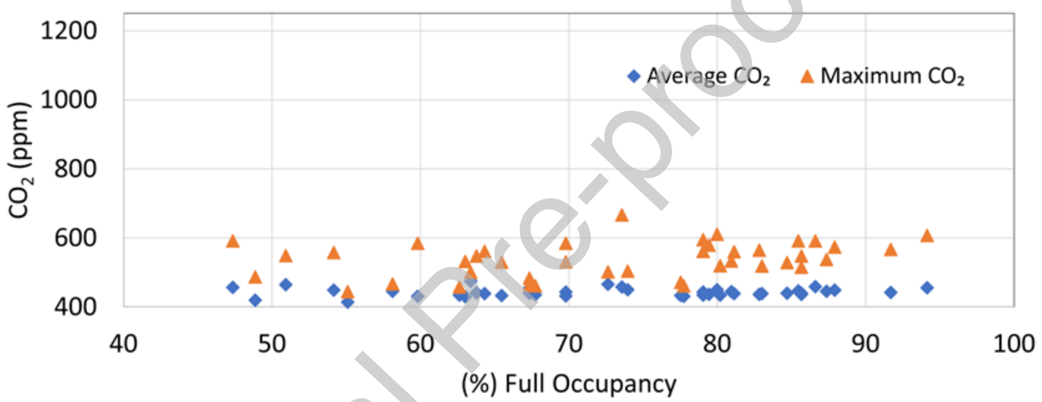


Figure 8: Spatiotemporal mean and point-in-time and space maximum CO_2 concentration and varying occupancy in the graduation marquee (LO) at all 41 events.

3.3.2 High occupancy marquee

In contrast in a densely occupied marquee, a clear association between high CO_2 concentrations and occupancy is observed (Figure 9). Spatially averaged CO_2 concentration, maximum CO_2, and occupant density measured in the middle zone of the music festival marquee were plotted in timeseries for one day (Figure 9). The CO_2 concentration and occupant density follow similar trends of increasing and decreasing over time. Rapid decreases in CO_2 in the marquee quickly followed declines in occupant density, as people left between performances. On most occasions, occupant density decreased to almost zero during these intervals, at which point the CO_2 concentration reduced to ambient levels in less than 15 minutes. As such, in this example, the spatiotemporal mean CO_2 concentration in this zone remained below 750 ppm throughout the observed period, but the maximum CO_2 concentrations tell a different story.

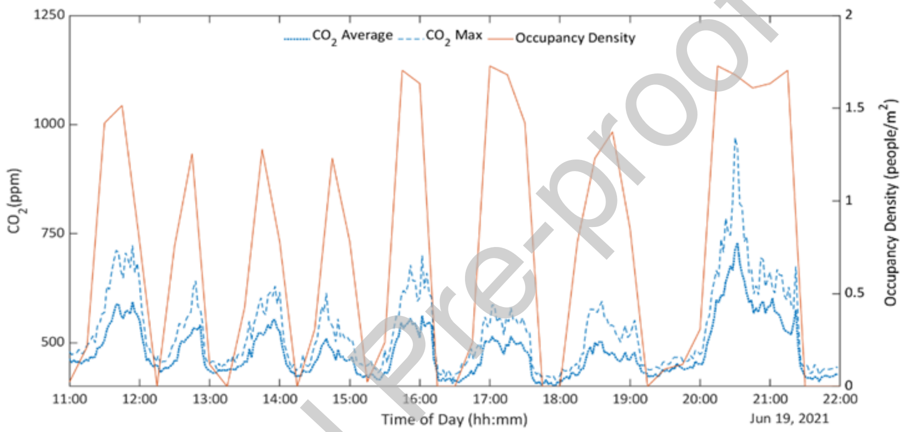


Figure 9: Occupancy density (calculated from CCTV imagery), spatial CO_2 average and spatial CO_2 maximum as a function of time in the middle zone at Download Festival (19 June).

3.4 The impact of occupant distribution and event management on indoor CO_2 concentration

It has been shown that the density of occupants in a space influences the concentration of CO_2 measured in the air (Section 3.3). This section presents evidence to show that whether occupants are free to move around a space or not influences the distribution of measured CO_2 (i.e., exhaled breath). The music festival tent, where occupants were free to move in, around, and out of the space, is compared to the graduation ceremony marquee, where occupants were seated throughout the event.

In the music festival tent, the CO_2 concentrations measured at different sensor locations varied by up to 520 ppm at any given time (Figure 10) compared to only 164 ppm at the graduation ceremony marquee[11] (Figure 11).

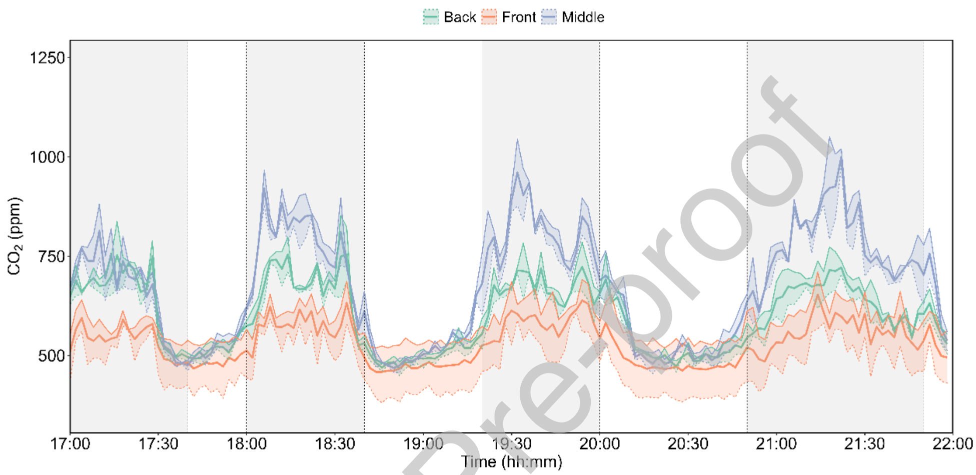


Figure 10: CO_2 concentration profile versus time in the music festival tent on Day one of the event (18 June 2021). Solid lines indicate the spatial average for each zone, with the shading indicating the minimum and maximum values. Greyed out sections indicate the scheduled music performance times.

[11] The greatest temporal variation in CO_2 concentration at a single graduation event was 282 ppm, which was not the day of greatest occupancy.

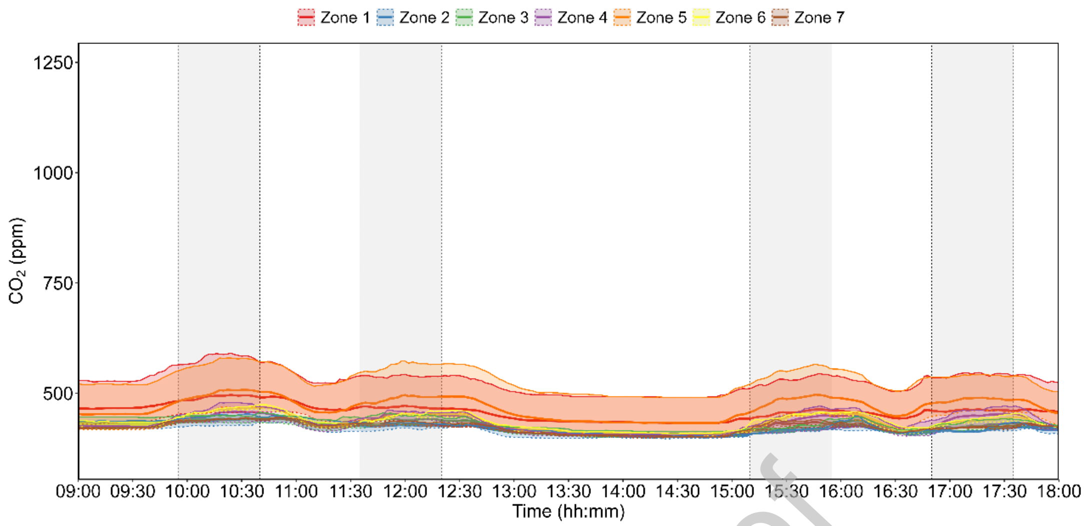


Figure 11: CO_2 concentration profile versus time of day in the graduation ceremony marquee on the day with the highest occupancy (486 people; 0.32 people/m^2). Solid lines indicate the spatial average for each zone, with the shading indicating the minimum and maximum values. Greyed sections indicate the ceremony times (four ceremonies on this day, usually five).

3.5 Comparison of two unstructured music events: indoors and semi-outdoors

A key question for the future management of mass gatherings is whether events held in semi-outdoor structures pose a lower risk for long-range airborne pathogen transmission compared to fully indoor venues, particularly in terms of ventilation. The CO_2 concentrations recorded at two music events with an unstructured audience are compared to establish this (Figure 12 and Figure 13). One was an indoor "nightclub" event held in a warehouse[12] and the other in comparison was a semi-outdoor music festival held in a

[12] The indoor nightclub event was also monitored as part of the ERP [15]. Data included CO_2 concentration and occupant density.

marquee. These events were chosen due to having a similar type of audience and activity (large groups of young people, unstructured, standing, and dancing), having a similar occupancy structure and because they were the two events with video occupancy analysis which allowed for calculation of spatiotemporal occupant density.

A timeseries shows CO_2 concentrations across the front, middle, and rear of the dancefloor of the indoor nightclub and at the semi-outdoor music festival marquee (Figure 12). CO_2 concentrations were consistently higher at the front section of the indoor nightclub and showed greater temporal and spatial variations than the semi-outdoor music festival.

In the indoor nightclub, CO_2 concentrations reached levels considerably higher (maximum >2000 ppm) compared to the semi-outdoor music event (maximum ~1000 ppm) (Figure 12). At the indoor nightclub, the front section had the highest CO_2 concentration, whereas this was found in the middle section of the semi-outdoor music festival marquee. Spatial variations in CO_2 concentration were greater in the indoor nightclub (range 1131 ppm, 79% relative to the mean) than at the semi-outdoor music festival (range 402 ppm, 50%).

Temporal variations in CO_2 concentration were observed at both events, with decreases in CO_2 concentration between music sets. These variations were greater in terms of absolute change in CO_2 concentration at the indoor nightclub, but they occurred over longer durations in the semi-outdoor music festival. The music festival had ca. 30 to 40 minutes between acts (Table 4) whereas the nightclub had an immediate changeover of acts (Table 6).

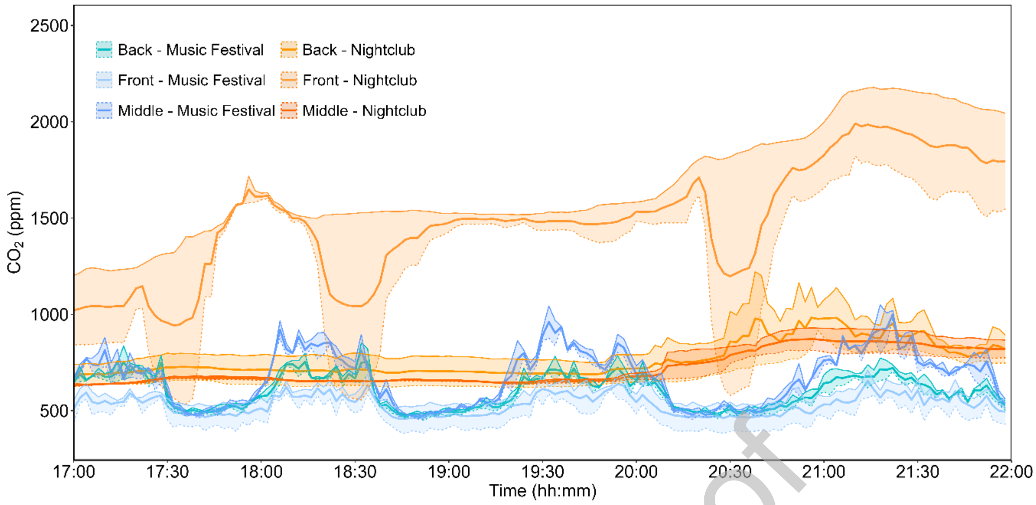
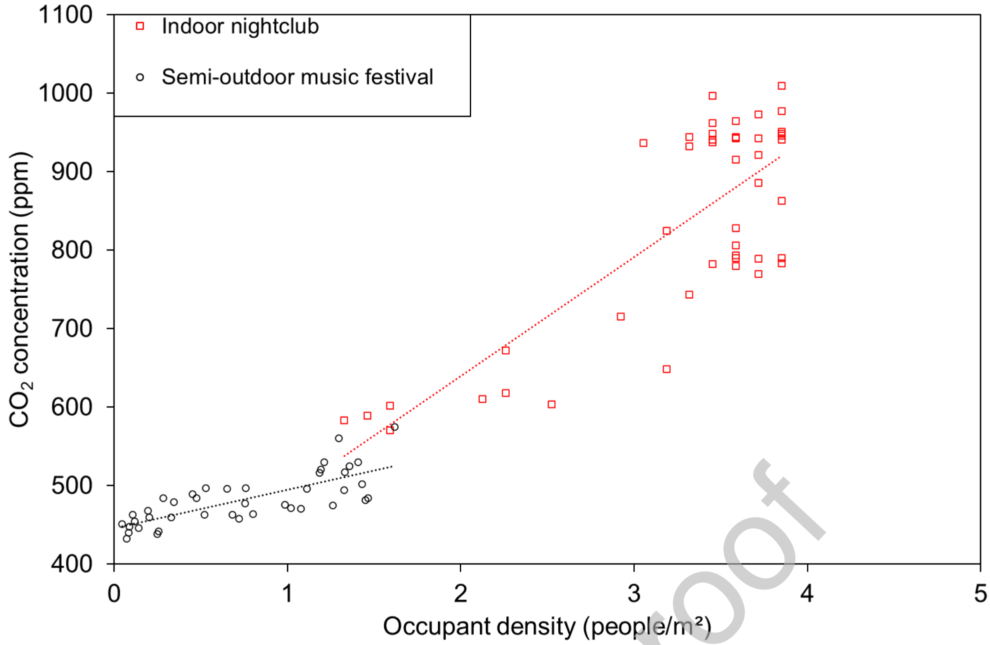


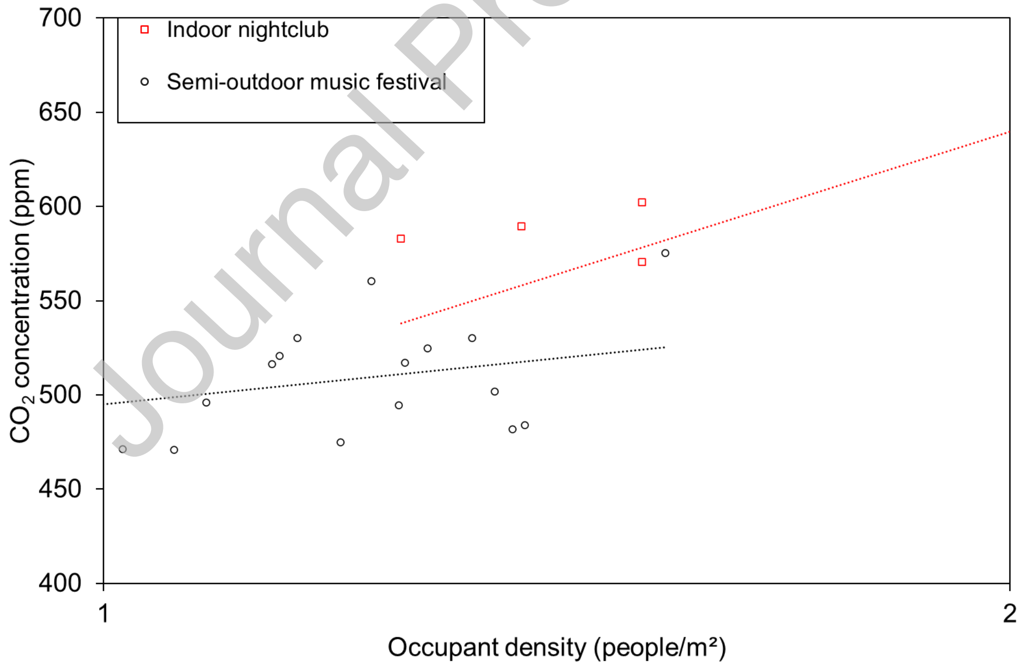
Figure 12: Comparison of CO_2 concentration versus time between two music events (D and NC) with an unstructured audience on the day with the highest occupancy (based on ticket sales: 1 May 2021). The nightclub event was at an indoor venue and the music festival was at a semi-outdoor venue. Solid lines indicate the spatial average for each zone with the shading indicating the minimum and maximum values recording at any single sensor in the zone.

The question as to whether the risk of long-range airborne pathogen transmission may be the same or different in indoor or semi-outdoor buildings with the same occupant densities can be further explored by comparing data on occupant density versus the recorded CO_2 concentration in the indoor nightclub and the semi-outdoor music festival (Figure 13). On these days, occupancy was recorded at 15-minute intervals between 11:00 and 22:00 in the music festival and at 5-minute intervals between 16:00 and 20:30 at the indoor nightclub. The maximum occupant density was 1.6 and 3.9 people/m^2 at the music festival and nightclub, respectively. The minimum occupant density at the nightclub was 1.3 people/m^2, and so there are several data points in each venue that overlap.

There is a positive correlation between occupant density and CO_2 concentration in both the semi-outdoor music festival and the indoor nightclub (Figure 13). Whilst CO_2 increases with occupancy in both spaces, it does so more rapidly in the nightclub. Focusing on the points where occupant densities are similar in both the indoor nightclub and semi-outdoor music festival, the CO_2 concentrations are generally higher in the indoor nightclub (Figure 13). The variation in CO_2 concentration at the indoor nightclub was higher when occupant density was higher (~ 3-4 people/m^2) compared to at 1-2 people/m^2, although there were more data points at the higher concentrations. In contrast, the CO_2 concentration at the semi-outdoor music festival varied less across all the occupant densities that were recorded.



(a) At the full range of occupant densities (0-5 people/m^2)



(b) A subset of data for occupant densities of 1-2 people/m^2.

Figure 13: The relationship between occupant density and mean spatial average CO_2 concentration at 15-minute intervals in the semi-outdoor music festival (11:00 to 22:00 18 June 2021) and at 5-minute intervals in the indoor nightclub (16:00 to 20:30 on 30 April 2021).

4 Discussion

Measurement of air quality relative to occupant density at high spatiotemporal resolution has shown, for the first time, that semi-outdoor spaces such as tents and marquees at mass gathering events were mostly well-ventilated relative to the occupancy levels. Some instances of poorer air quality were identified, however. The research gathered data across eight[13] venues at 78 semi-outdoor and 2 indoor events to provide the largest dataset in existence worldwide. By combining data from multiple calibrated CO_2 sensors distributed around each venue with occupant density measurements from video analysis and supported by ticket scan counting, a high-quality dataset has been created. This robust evidence can, for the first time, inform new building regulations and event management strategies that ensure acceptable indoor air quality at semi-outdoor mass gathering events. This will help protect the health and wellbeing of event attendees and, ultimately, the wider population with respect to long-range transmission of airborne disease.

Using an established rapid air quality assessment methodology [15], this study demonstrated that all the semi-outdoor spaces had always at least "medium" air quality across the whole venue. Whilst CO_2 concentration is a widely used indicator for the rebreathed air fraction [53], on its own it does not directly correlate to airborne infection risk [68]. Nonetheless, during the COVID-19 pandemic, the UK Government's Scientific Advisory Group for Emergencies (SAGE) advised that CO_2 concentrations less than 1500 ppm indicated acceptable levels of ventilation [69]. Following that definition, all semi-outdoor spaces in this study were acceptably ventilated, but the indoor space was not. This indicates that semi-indoor mass gathering event spaces potentially have a

[13] Seven semi-outdoor, one indoor.

lower long-range airborne infection risk than indoor spaces, but this is dependent upon the probability of an infector being in the space, their viral emission rate, and the occupancy which modifies the population level risk [13,70,71].

Although the spaces monitored were defined as semi-outdoor, the ventilation provision did not result in CO_2 concentrations equivalent to outdoor levels. In all spaces, CO_2 concentration increased above ambient levels when occupied. Therefore, it cannot be assumed that semi-outdoor spaces present the same risk of long-range aerosol transmission as fully outdoor spaces, as evidenced by the overall classifications in Figures 4 and 5.

Nevertheless, semi-outdoor spaces are frequently used to host mass gathering events, and the overall findings should give event managers confidence to continue using these types of spaces with respect to long-range airborne infections during periods when transmission of pathogens is of concern, subject to several caveats. These caveats primarily relate to how the spaces are operated, including the size of natural ventilation openings and mechanical ventilation rates, and the way they are occupied. These operational factors are further discussed in the following sections.

4.1 The influence of varying ventilation rates in marquees

4.1.1 Natural ventilation

Air quality conditions can vary in marquees depending on how the ventilation provision is designed and used. In most cases, large natural ventilation openings ensured that the spaces were ventilated so that occupants' exposure to exhaled breath was reduced to acceptable levels of air quality (i.e., air quality classification bands A-C). In some examples, such as the graduation marquee, the openings were so large (alongside low occupant density) that the average CO_2 concentrations were comparable to those of a fully outdoor space, even when close to 100% occupancy[14] (Figure 8). This demonstrates the ability for semi-outdoor buildings to provide shelter for the occupants whilst maintaining air quality levels close to that of outdoors[15].

Whilst acceptable air quality can be achieved in semi-outdoor buildings, it was observed that during cold or wet weather, the closure of the natural ventilation openings in some hospitality marquees was detrimental to the indoor air quality. Because marquees are usually enclosed by an air-impermeable barrier, apart from some purpose-provided openings for access and ventilation, ventilation rates will be lower when marquee side openings are closed or when ventilation is otherwise restricted. An example from The Grange Theatre marquees (Figure 7) illustrates that CO_2 concentrations were higher on a rainy day compared to a day without rain in the same marquee, despite occupancy levels being similar. Two factors may explain this difference. First, the researchers on site observed that the side flaps on the marquees were closed to attempt to keep dry and attain satisfactory thermal comfort for the occupants on the day with inclement weather. In contrast, on the day without rain, the flaps were kept open, and ventilation into the marquee was more easily permitted. This has been similarly observed studies of indoor venues where ventilation openings were closed to prevent noise egress from music venues [15,72]. The second factor explaining the difference is that it is plausible that more people used the marquee to shelter from the rain, leading to a temporary increase in occupancy, and a higher rate of CO_2 exhalation in the space.

[14] Occupancy was restricted for this seated audience and feasibly, occupancy capacity could have been far higher.

[15] The greatest temporal increase in CO_2 concentration ceremony was 242 ppm, showing that the exhaling occupants did slightly increase the exposure to exhaled breath during some events. Rapid decays in CO_2 concentration after the event infers that ventilation rates were high in this marquee which was fully open on three sides and had no internal partitions (Figure 17).

4.1.2 Mechanical ventilation

In this study, most event venues were naturally ventilated, but the two marquees at Ascot racecourse were mechanically ventilated (Table 1). Importantly, mechanical ventilation did not guarantee better air quality than in the naturally ventilated venues. In fact, one of the Ascot marquees (RA5) had the poorest air quality of all the semi-outdoor buildings monitored (Figure 5). The way the ventilation was operated in response to weather influenced the air quality, just as it did in the naturally ventilated semi-outdoor buildings (Section 4.1.1).

In the Ascot RA5 marquee, on warmer days, much lower CO_2 concentrations of 550 ppm were recorded. This was most likely due to an increase in supply of cooled air into the venue in response to hot weather (Figure 7) which rose from 1.5 air changes per hour on cooler days to 5 air changes per hour on warmer days (see [56] for calculations of ventilation rate via CO_2 decay). This demonstrates that the mechanical ventilation in place was sufficient to dilute the exhaled breath of the occupants, but was operated at insufficient levels on some days. Whilst the sample size of five event days is too small to perform statistical analyses, the two example days suggest that ventilation management strategy in mechanically ventilated semi-outdoor buildings can affect the ventilation rate and so, the indoor air quality.

4.2 Event management strategies: Occupant distribution

Spatial variations in occupant exposure to air quality were more pronounced at the music festival than in the other semi-outdoor venues. The audience at the music festival was unstructured and free to move about the space which created heterogeneous crowd densities. In contrast, the occupants in the other semi-outdoor event venues were seated and more uniformly distributed (Table 1).

Previous work has attributed spatial variations in CO_2 concentration at indoor theatre events to poor ventilation effectiveness. For example, in a theatre, the mechanical ventilation system supplied air at floor level and extracted at ceiling level, which exposed those in the upper tiers of the theatre auditoria seating to higher concentrations of CO_2 [55]. The present study, however, identified an additional factor and points towards how occupants are distributed within a space as affecting the spatial variation in CO_2 concentration (exhaled breath). This finding highlights the importance of occupancy distribution alongside the ventilation strategy in determining the spatial distribution of air quality, and supports the observations of Malki-Epshtein et al. [15] on occupancy influences for indoor spaces.

However, whilst controlling occupant density and distribution at mass gatherings using seated events can influence the spatial variability of CO_2, it does not necessarily result in a lower absolute CO_2 concentration. This study showed that a seated event (hospitality marquee Ascot RA5) recorded the highest maximum CO_2 concentration (1151 ppm) of all semi-outdoor buildings monitored. This indicates that ventilation provision is important regardless of how the occupants are distributed. Therefore, each building should be assessed individually for its ventilation provision to ensure that CO_2 concentrations (and exposure to exhaled breath) remain at acceptable levels, rather than relying on controlling occupant density and distribution alone.

4.3 Event management strategies: use of intervals

CO_2 concentration decreased, often rapidly, as occupancy ceased. This observation demonstrates that intervals[16] are a worthwhile intervention to reduce exposure to exhaled breath between events. The benefits of intervals have been shown at indoor

[16] Intervals are breaks during the event. E.g., periods where the venue is unoccupied between sets at the music festival or between graduation ceremonies.

events (theatre venues) [55]. The present study shows that intervals are also useful in semi-outdoor spaces, although a much shorter duration is required compared to indoor spaces due to the generally higher ventilation rates in semi-outdoor buildings. For example, at the music festival CO_2 concentrations fell by 50% from around 850 ppm to ambient levels (ca. 430 ppm) within 15 minutes (Figure 9). In contrast, intervals at indoor theatre events, in some cases, did not reduce CO_2 concentrations below 1250 ppm during a 30-minute interval [55].

Therefore, in the semi-outdoor buildings monitored in this study, the intervals of up to 70 minutes were unnecessary for the purposes of reducing airborne infection risk, but otherwise necessary to allow time for the next performer to set up their equipment and for the audience to return from performances at other performance stages at the festival. Similarly, at the graduation ceremonies, intervals of 55 to 70 minutes were unnecessary as the ventilation provision was already sufficient during occupancy, but it did provide time for the sanitation of contact points such as chairs to reduce potential fomite transmission.

4.4 Are semi-outdoor buildings better ventilated than indoor events? A comparison of two unstructured music events

This study compared an indoor nightclub to a semi-outdoor music festival marquee. Both venues had similar occupancy structures, with an audience that was free to move in, out, and around the space whilst watching a music performance. The two venues had distinctly different ventilation characteristics that were influenced by the building design: the nightclub was an enclosed building and the music festival was an open-sided marquee. It is important to state that the occupant density was, however, generally higher at the indoor nightclub, and so care must be taken to interpret the CO_2

concentrations whilst considering the occupant density. There were several datapoints where occupant density was similar in the indoor nightclub and semi-outdoor music festival, however (Figure 13 13).

The overlapping occupant densities in the two venues occur at around 1.5 p/m^2, at which point occupants may still move freely [65]. Here, the CO_2 concentrations were generally higher in the indoor nightclub which suggests a lower ventilation rate relative to the occupancy compared to the semi-outdoor music festival marquee. More data at a range of overlapping occupant densities in the two venues would strengthen this inference.

Equally, it could be argued that simply controlling occupant density by limiting attendees is an effective strategy to ensure acceptable indoor air quality with respect to long-range aerosol transmission. This argument is supported by modelling of large sport event audiences [39]. Nonetheless, the primary difference between the two venues was the large natural ventilation openings in the music festival marquee which allowed the occupied space to be cross-ventilated. Cross-ventilation has been shown to be effective for increasing ventilation rates compared to single-sided ventilation [73,74].

Other work noted that issues around noise pollution also limit event organisers utilising larger natural ventilation openings [15,72]. In this case, the indoor nightclub was restricted to keeping many openings closed to prevent noise nuisance from the loud sound systems, whilst the festival was located away from property and had different noise abatement requirements enabling large portions of the side of the marquee tent to remain open. This demonstrates that the choice of mass gathering event venue, and the ventilation strategy used, is important to limit occupant exposure to exhaled breath (which may contain virus-laden aerosols).

4.5 Limitations and further work

A key strength of the monitoring study was the use of calibrated sensors at a high spatiotemporal resolution – up to 33 sensors were installed in a single space at any one time (Section 2.3). This allowed for rapid (2-minutely) changes in CO_2 concentrations to be observed and spatial variation to be detected. However, sensor placement was constrained by available mounting locations in some venues. For example, at most venues, there was only space to hang the sensors on the perimeter walls, but at the music festival support poles in the centre of the crowd were also used (Figure 16) and at the graduation ceremony they were mounted on chairs (Figure 20). The positioning of sensors may influence the uncertainty in the spatially average CO_2 concentrations, with the music festival and graduation marquees having higher spatial representativeness than other venues. Future work could assess how representative single-point CO_2 measurements are of entire occupied zones, comparing perimeter and central placements. Work to this end has been done in school classrooms [75], where it is common to have only one CO_2 sensor. The multi-sensor data from this study may be useful for such analyses, alongside controlled laboratory validation.

Due to the events being monitored during the COVID-19 pandemic, some had reduced occupancy. While several venues reached near or full capacity (Table 1)[17], others, like the nightclub, operated at 50% capacity. Nonetheless, this does not diminish the quality of the findings, and the evidence suggests that even when occupancy was reduced, the free movement of people in the space meant that crowding still occurred on the dancefloor at occupant densities close to what is considered the maximum for comfort (see Section 2.5).

[17] The Loughborough graduation marquee was up to 94% occupied, but the total capacity was a reduced below the true holding capacity to comply with COVID-19 risk assessments.

The non-interventionist nature of this field study enabled observation of real-world conditions but limited the ability to isolate effects such as occupancy versus venue design. For example, generally higher occupant densities in the nightclub (dancefloor) limited direct comparison with the music festival as there were only a few overlapping incidences of the same occupant density. Therefore, it was not straightforward to confidently assert that under the same occupant densities one venue would have a lower CO_2 concentration than the other at a range of occupant densities that could be expected within the range of occupant comfort [65]. Future work could consider how vertical distribution of CO_2 varies in space considering occupancy density per unit of volume as well as floor area. Experimental studies with controlled ventilation and occupancy may help resolve these limitations.

While the study assumes higher ventilation reduces infection risk, actual transmission risk was beyond scope, given uncertainties around infectious individuals and emission rates. Quantification of long-range airborne infection risk was beyond the scope of this paper, but it has been considered elsewhere [13,14,56,70]. Nonetheless, overcrowding can also contribute to risk. The dataset collected may support future work on airborne infection modelling

4.6 Future regulations around semi-outdoor buildings and temporary structures

Semi-outdoor, temporary buildings are currently not considered in regulations related to ventilation, air quality, and airborne infection transmission. This work has shown that when purpose-provided ventilation openings were closed or when mechanical ventilation rates were reduced, the air quality reduces. Therefore, the assumption that semi-outdoor buildings are universally well-ventilated is wrong. These types of buildings do not have any inherent properties which make them any better ventilated than an indoor space other than the potential to have very large ventilation openings.

Given their widespread use as mass gathering events, there is a clear need for the design and operation of semi-outdoor, temporary structures to be included in future regulations and this work provides key evidence to inform such regulations. Regulation to ensure sufficient ventilation is just as necessary for semi-outdoor buildings as it is for any other building type. Future pandemic preparedness plans would be wise to include the use of semi-outdoor temporary buildings for hosting mass gatherings, but should include robust ventilation strategies such as large natural ventilation openings or mechanical ventilation which generates sufficient quantities of outdoor air into the space. Operated in this way, semi-outdoor buildings can be used as temporary structures at mass gathering event to reduce the risk of long-range airborne transmission of pathogens and protect attendees and the wider population from the spread of disease, such as COVID-19.

5 Conclusion

In the largest monitoring campaign of its type conducted worldwide, this study provided the first crucial evidence to assess the provision of ventilation in semi-outdoor venues for mass gathering events, such as marquees. Previous evidence on ventilation provision in semi-outdoor spaces was scarce, so this paper fills an important gap in the literature. The work made a significant contribution to government risk assessments regarding reopening mass gathering events after the COVID-19 pandemic. This paper showed that most semi-outdoor event venues were sufficiently ventilated relative to the occupancy, such that air quality with respect to long-range transmission of SARS-CoV-2, was deemed to be within acceptable levels of risk (spatiotemporal average CO_2 concentration <800 ppm).

There were instances, however, where high CO_2 concentrations (1,151 ppm) were measured due to poor ventilation management or crowding in densely occupied spaces, but these were lower than the >2000 ppm recorded at a similar indoor venue. The work highlighted the importance of careful event management and consideration given to the way the semi-outdoor buildings are ventilated. With ventilation restricted, semi-outdoor buildings are not inherently low-risk with respect to long-range airborne pathogen transmission and so require careful consideration for the ventilation provision relative to the occupancy.

As such, this research recommends that semi-outdoor buildings continue to be used at mass-gathering and high-occupancy events, but that building regulations and event management strategies consider these types of buildings. Utilising the largest field study of its kind worldwide, this work provides key evidence to inform such regulations. With this new knowledge, the spread of airborne pathogens can be reduced to protect the health and wellbeing of those attending mass gathering events, and the wider population from major pandemics.

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8 References

[1] E. Mathieu, H. Ritchie, L. Rodés-Guirao, C. Appel, C. Giattino, J. Hasell, B. Macdonald, S. Dattani, D. Beltekian, E. Ortiz-Ospina, M. Roser, Coronavirus Pandemic (COVID-19), Published Online at OurWorldInData.Org (2025). https://ourworldindata.org/coronavirus (accessed June 5, 2023).

[2] S.H. Ebrahim, Z.A. Memish, COVID-19 – the role of mass gatherings, Travel Med Infect Dis 34 (2020) 101617. https://doi.org/10.1016/J.TMAID.2020.101617.

[3] M. Brandl, R. Selb, S. Seidl-Pillmeier, D. Marosevic, U. Buchholz, S. Rehmet, Mass gathering events and undetected transmission of SARS-CoV-2 in vulnerable populations leading to an outbreak with high case fatality ratio in the district of Tirschenreuth, Germany, Epidemiol Infect (2020). https://doi.org/10.1017/S0950268820002460.

[4] N.F. Che Mat, H.A. Edinur, M.K.A. Abdul Razab, S. Safuan, A single mass gathering resulted in massive transmission of COVID-19 infections in Malaysia with further international spread, J Travel Med 27 (2020). https://doi.org/10.1093/jtm/taaa059.

[5] S. Cuschieri, M. Balzan, C. Gauci, S. Aguis, V. Grech, Mass Events Trigger Malta's Second Peak After Initial Successful Pandemic Suppression, J Community Health 46 (2021) 618–625. https://doi.org/10.1007/S10900-020-00925-6/TABLES/1.

[6] S. Domènech-Montoliu, M.R. Pac-Sa, P. Vidal-Utrillas, M. Latorre-Poveda, A. Del Rio-González, S. Ferrando-Rubert, G. Ferrer-Abad, M. Sánchez-Urbano, L. Aparisi-Esteve, G. Badenes-Marques, B. Cervera-Ferrer, U.

Clerig-Arnau, C. Dols-Bernad, M. Fontal-Carcel, L. Gomez-Lanas, D. Jovani-Sales, M.C. León-Domingo, M.D. Llopico-Vilanova, M. Moros-Blasco, C. Notari-Rodríguez, R. Ruíz-Puig, S. Valls-López, A. Arnedo-Pena, “Mass gathering events and COVID-19 transmission in Borriana (Spain): A retrospective cohort study,” PLoS One 16 (2021) e0256747. https://doi.org/10.1371/journal.pone.0256747.

[7] M. Stange, A. Marii, T. Roloff, H.M.B. Seth-Smith, M. Schweitzer, M. Brunner, K. Leuzinger, K.K. SÃgaard, A. Gensch, S. Tschudin-Sutter, S. Fuchs, J. Bielicki, H. Pargger, M. Siegemund, C.H. Nickel, R. Bingisser, M. Osthoff, S. Bassetti, R. Schneider-Sliwai, M. Battegay, H.H. Hirschi, A. Egli, SARS-CoV-2 outbreak in a tri-national urban area is dominated by a B.1 lineage variant linked to a mass gathering event, PLoS Pathog 17 (2021) e1009374. https://doi.org/10.1371/JOURNAL.PPAT.1009374.

[8] D. Yusef, W. Hayajneh, S. Awad, S. Momany, B. Khassawneh, S. Samrah, B. Obeidat, L. Raffee, I. Al-Faouri, A. Bani Issa, H. Al Zamel, E. Bataineh, R. Qdaisat, Large Outbreak of Coronavirus Disease among Wedding Attendees, Jordan - Volume 26, Number 9—September 2020 - Emerging Infectious Diseases journal - CDC, Emerg Infect Dis 26 (2020) 2165–2167. https://doi.org/10.3201/EID2609.201469.

[9] R. González-Val, M. Marcén, Mass gathering events and the spread of infectious diseases: Evidence from the early growth phase of COVID-19, Econ Hum Biol 46 (2022) 101140. https://doi.org/10.1016/J.EHB.2022.101140.

[10] N. Sugano, W. Ando, W. Fukushima, Cluster of Severe Acute Respiratory Syndrome Coronavirus 2 infections linked to music clubs in Osaka, Japan, Journal of Infectious Diseases 222 (2020) 1635–1640. https://doi.org/10.1093/infdis/jiaa542.

[11] C.R. Kang, J.Y. Lee, Y. Park, I.S. Huh, H.J. Ham, J.K. Han, J. Il Kim, B.J. Na, Coronavirus Disease Exposure and Spread from Nightclubs, South Korea, Emerging Infectious Disease Journal 26 (2020) 2499. https://doi.org/10.3201/eid2610.202573.

[12] S. Tang, Y. Mao, R.M. Jones, Q. Tan, J.S. Ji, N. Li, J. Shen, Y. Lv, L. Pan, P. Ding, X. Wang, Y. Wang, C.R. MacIntyre, X. Shi, Aerosol transmission of SARS-CoV-2? Evidence, prevention and control, Environ Int 144 (2020) 106039. https://doi.org/10.1016/J.ENVINT.2020.106039.

[13] C. Iddon, B. Jones, P. Sharpe, M. Cevik, S. Fitzgerald, A population framework for predicting the proportion of people infected by the far-field airborne transmission of SARS-CoV-2 indoors, Build Environ 221 (2022) 109309. https://doi.org/10.1016/J.BUILDENV.2022.109309.

[14] B. Jones, P. Sharpe, C. Iddon, E.A. Hathway, C.J. Noakes, S. Fitzgerald, Modelling uncertainty in the relative risk of exposure to the SARS-CoV-2 virus by airborne aerosol transmission in well mixed indoor air, Build Environ 191 (2021) 107617. https://doi.org/10.1016/J.BUILDENV.2021.107617.

[15] L. Malki-Epshtein, F. Adzic, B.M. Roberts, E. Abigail Hathway, C. Iddon, M. Mustafa, M. Cook, Measurement and rapid assessment of indoor air quality at mass gathering events to assess ventilation performance and reduce aerosol transmission of SARS-CoV-2, Building Services Engineering Research & Technology 44 (2023) 113–133. https://doi.org/10.1177/01436244221137995.

[16] S.L. Miller, W.W. Nazaroff, J.L. Jimenez, A. Boerstra, G. Buonanno, S.J. Dancer, J. Kurnitski, L.C. Marr, L. Morawska, C. Noakes, Transmission of SARS-CoV-2 by inhalation of respiratory aerosol in the Skagit Valley Chorale superspreading event, Indoor Air 31 (2021) 314–323. https://doi.org/10.1111/INA.12751.

[17] G. Buonanno, L. Stabile, L. Morawska, Estimation of airborne viral emission: Quanta emission rate of SARS-CoV-2 for infection risk assessment, Environ Int 141 (2020) 105794. https://doi.org/10.1016/J.ENVINT.2020.105794.

[18] L. Wang, T. Lin, H. Da Costa, S. Zhu, T. Stockman, A. Kumar, J. Weaver, M. Spede, D.K. Milton, J. Hertzberg, D.W. Toohey, M.E. Vance, S.L. Miller, J. Srebric, Characterization of aerosol plumes from singing and playing

wind instruments associated with the risk of airborne virus transmission, Indoor Air 32 (2022) e13064. https://doi.org/10.1111/INA.13064.

[19] B. Saccente-Kennedy, J. Archer, H.E. Symons, N.A. Watson, C.M. Orton, W.J. Browne, J. Harrison, J.D. Calder, P.L. Shah, D. Costello, J.P. Reid, B.R. Bzdek, R. Epstein, Quantification of Respirable Aerosol Particles from Speech and Language Therapy Exercises, Journal of Voice (2022). https://doi.org/10.1016/j.jvoice.2022.07.006.

[20] J. Archer, L.P. McCarthy, H.E. Symons, N.A. Watson, C.M. Orton, W.J. Browne, J. Harrison, B. Moseley, K.E.J. Philip, J.D. Calder, P.L. Shah, B.R. Bzdek, D. Costello, J.P. Reid, Comparing aerosol number and mass exhalation rates from children and adults during breathing, speaking and singing, Interface Focus 12 (2022). https://doi.org/10.1098/rsfs.2021.0078.

[21] M. Alsved, A. Matamis, R. Bohlin, M. Richter, P.-E. Bengtsson, C.-J. Fraenkel, P. Medstrand, J. Löndahl, Exhaled respiratory particles during singing and talking, Aerosol Science and Technology 54 (2020) 1245–1248.

[22] J. Schijven, L.C. Vermeulen, A. Swart, A. Meijer, E. Duizer, A.M. de Roda Husman, Quantitative microbial risk assessment for airborne transmission of SARS-CoV-2 via breathing, speaking, singing, coughing, and sneezing, Environ Health Perspect 129 (2021) 047002.

[23] The Prime Minister’s Office, Prime Minister’s statement on coronavirus (COVID-19): 23 March 2020, (2020). https://www.gov.uk/government/speeches/pm-address-to-the-nation-on-coronavirus-23-march-2020 (accessed June 6, 2023).

[24] J.M. Brauner, S. Mindermann, M. Sharma, D. Johnston, J. Salvatier, T. Gavenčiak, A.B. Stephenson, G. Leech, G. Altman, V. Mikulik, A.J. Norman, J.T. Monrad, T. Besiroglu, H. Ge, M.A. Hartwick, Y.W. Teh, L. Chindelevitch, Y. Gal, J. Kulveit, Inferring the effectiveness of government interventions against COVID-19, Science (1979) 371 (2021). https://doi.org/10.1126/science.abd9338.

[25] UK Music, UK Music Submission to House of Commons DCMS Select Committee Inquiry on Impact of COVID-19 on DCMS Sectors, (2020). https://committees.parliament.uk/writtenevidence/4435/html/ (accessed June 6, 2023).

[26] G. Burnside, C.P. Cheyne, G. Leeming, M. Humann, A. Darby, M.A. Green, A. Crozier, S. Maskell, K. O'Halloran, E. Musi, E. Carmi, N. Khan, D. Fisher, R. Corcoran, J. Dunning, W.J. Edmunds, K. Tharmaratnam, D.M. Hughes, L. Malki-Epshtein, M. Cook, B.M. Roberts, E. Gallagher, K. Howell, M. Chand, R. Kemp, M. Boulter, T. Fowler, M.G. Semple, E. Coffey, M. Ashton, M. García-Fiñana, I.E. Buchan, COVID-19 risk mitigation in reopening mass cultural events: population-based observational study for the UK Events Research Programme in Liverpool City Region, J R Soc Med (2023). https://doi.org/10.1177/01410768231182389.

[27] T. Salthammer, H. Moriske, Airborne infections related to virus aerosol contamination at indoor cultural venues: Recommendations on how to minimize, Public Health Challenges 2 (2023). https://doi.org/10.1002/puh2.59.

[28] H. Dai, B. Zhao, Association of the infection probability of COVID-19 with ventilation rates in confined spaces, Building Simulation 2020 13:6 13 (2020) 1321–1327. https://doi.org/10.1007/S12273-020-0703-5.

[29] A. Di Gilio, J. Palmisani, M. Pulimeno, F. Cerino, M. Cacace, A. Miani, G. de Gennaro, CO2 concentration monitoring inside educational buildings as a strategic tool to reduce the risk of Sars-CoV-2 airborne transmission, Environ Res 202 (2021) 111560. https://doi.org/10.1016/J.ENVRES.2021.111560.

[30] L. Morawska, J. Cao, Airborne transmission of SARS-CoV-2: The world should face the reality, Environ Int 139 (2020) 105730. https://doi.org/10.1016/J.ENVINT.2020.105730.

[31] P. Azimi, Z. Keshavarz, J.G. Cedeno Laurent, B. Stephens, J.G. Allen, Mechanistic transmission modeling of COVID-19 on the Diamond Princess

cruise ship demonstrates the importance of aerosol transmission, Proc Natl Acad Sci U S A 118 (2021) e2015482118. https://doi.org/10.1073/PNAS.2015482118/SUPPL_FILE/PNAS.2015482118.SAPP.PDF.

[32] A. Madhusudanan, C. Iddon, M. Cevik, J.H. Naismith, S. Fitzgerald, Non-pharmaceutical interventions for COVID-19: A systematic review on environmental control measures, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 381 (2023). https://doi.org/10.1098/rsta.2023.0130.

[33] A. Hajaali, T. Stoesser, S. Fitzgerald, Cloud and droplet dynamics during a human coughing event under fully mixed and unmixed room conditions, Physics of Fluids 36 (2024) 023345. https://doi.org/10.1063/5.0185686.

[34] B. Revollo, I. Blanco, P. Soler, J. Toro, N. Izquierdo-Useros, J. Puig, X. Puig, V. Navarro-Pérez, C. Casañ, L. Ruiz, D. Perez-Zsolt, S. Videla, B. Clotet, J.M. Llibre, Same-day SARS-CoV-2 antigen test screening in an indoor mass-gathering live music event: a randomised controlled trial, Lancet Infect Dis 21 (2021) 1365–1372. https://doi.org/10.1016/S1473-3099(21)00268-1.

[35] M. Harris, J. Kreindler, A. El-Osta, T. Esko, A. Majeed, Safe management of full-capacity live/mass events in COVID-19 will require mathematical, epidemiological and economic modelling, J R Soc Med 114 (2021) 290–294. https://doi.org/10.1177/01410768211007759/ASSET/IMAGES/LARGE/10.1177_01410768211007759-FIG1.JPEG.

[36] I.J. Douglas, J. Peh, K.E. Mansfield, A. Trelfa, T. Fowler, M. Boulter, P. Cleary, J. Smith, W.J. Edmunds, A self-controlled case series study to measure the risk of SARS-CoV-2 infection associated with attendance at sporting and cultural events: the UK Events Research Programme events, BMC Med 22 (2024) 100. https://doi.org/10.1186/s12916-024-03276-4.

[37] M. Liao, H. Liu, X. Wang, X. Hu, Y. Huang, X. Liu, K. Brenan, J. Mecha, M. Nirmalan, J.R. Lu, A technical review of face mask wearing in preventing

respiratory COVID-19 transmission, Curr Opin Colloid Interface Sci 52 (2021) 101417. https://doi.org/10.1016/J.COCIS.2021.101417.

[38] C. Delaugerre, F. Foissac, H. Abdoul, G. Masson, L. Choupeaux, E. Dufour, N. Gastli, S.M. Delarue, M.L. Néré, M. Minier, A. Gabassi, M. Salmona, M. Seguineau, S. Schmitt, S. Tonglet, A. Olivier, C. Poyart, J. Le Goff, X. Lescure, S. Kernéis, J.M. Tréluyer, Prevention of SARS-CoV-2 transmission during a large, live, indoor gathering (SPRING): a non-inferiority, randomised, controlled trial, Lancet Infect Dis 22 (2022) 341–348. https://doi.org/10.1016/S1473-3099(21)00673-3.

[39] T. Yasutaka, M. Murakami, Y. Iwasaki, W. Naito, M. Onishi, T. Fujita, S. Imoto, Assessment of COVID-19 risk and prevention effectiveness among spectators of mass gathering events, Microb Risk Anal 21 (2022). https://doi.org/10.1016/j.mran.2022.100215.

[40] A. Cheshmehzangi, Z. Su, R. Jin, A. Dawodu, M. Sedrez, S. Pourroostaei Ardakani, T. Zou, Space and social distancing in managing and preventing COVID-19 community spread: An overview, Heliyon 9 (2023). https://doi.org/10.1016/j.heliyon.2023.e13879.

[41] C.M. and S. Department for Digital, Events Research Programme: Phase I findings, Online (2021). https://www.gov.uk/government/publications/events-research-programme-phase-i-findings/events-research-programme-phase-i-findings (accessed September 30, 2022).

[42] P.R. Hunter, F.J. Colón-González, J. Brainard, S. Rushton, Impact of non-pharmaceutical interventions against COVID-19 in Europe in 2020: a quasi-experimental non-equivalent group and time series design study, Eurosurveillance 26 (2021) 2001401. https://doi.org/10.2807/1560-7917.

[43] Office for National Statistics, Coronavirus and the social impacts on Great Britain: 14 May 2021, (2021). https://www.ons.gov.uk/peoplepopulationandcommunity/healthandsocialcare/healthandwellbeing/bulletins/coronavirusandthesocialimpactsongreatbritain/14may2021 (accessed June 6, 2023).

[44] MUTA, Best Practice Guide - Safe Use and Operation of Temporary Demountable Fabric Structures, 2018. www.muta.org.uk.

[45] HM Government, The Health Act 2006, HM Government, 2006. https://www.legislation.gov.uk/ukpga/2006/28 (accessed July 31, 2025).

[46] BBC, COVID-19: Pub marquees could become permanent fixtures, BBC News Website (2021). https://www.bbc.co.uk/news/uk-58452949 (accessed June 4, 2023).

[47] UK Government, Coronavirus (COVID-19): How to safely plan a wedding or civil partnership, or funeral, wake or commemoration, (2021). Coronavirus (COVID-19): How to safely plan a wedding or civil partnership, or funeral, wake or commemoration (accessed June 4, 2023).

[48] H. and C. Department for Levelling Up, Boost for high streets and businesses as markets and outdoor marquees allowed permanently, (2021). https://www.gov.uk/government/news/boost-for-high-streets-and-businesses-as-markets-and-outdoor-marquees-allowed-permanently#:~:text=Boost%20for%20high%20streets%20and%20businesses%20as,and%20town%20centres%20and%20boost%20local%20businesses. (accessed June 4, 2023).

[49] BSI, BS EN 13782:2015 - TC - Temporary structure. Tents. Safety, 2015. https://knowledge.bsigroup.com/products/temporary-structure-tents-safety?version=tracked&tab=overview (accessed January 30, 2024).

[50] Events Industry Forum, Keeping workers and audiences safe during COVID-19 in the outdoor event industry in England, 2021. https://www.eventsindustryforum.co.uk/images/documents/EIF-DCMS-COVID-19-Working-Safely-11-March-2021.pdf (accessed June 4, 2023).

[51] A.J. Persing, B. Roberts, J.T. Lotter, E. Russman, J. Pierce, Evaluation of ventilation, indoor air quality, and probability of viral infection in an outdoor dining enclosure, J Occup Environ Hyg 19 (2022) 302–309. https://doi.org/10.1080/15459624.2022.2053692/SUPPL_FILE/UOEH_A_2053692_SM7663.DOCX.

[52] A.K. Persily, Field measurement of ventilation rates, Indoor Air (2015) 97–111. https://doi.org/10.1111/ina.12193.

[53] Z. Peng, J.L. Jimenez, Exhaled CO2 as a COVID-19 infection risk proxy for different indoor environments and activities, Environ Sci Technol Lett 8 (2021) 392–397. https://doi.org/https://doi.org/10.1021/acs.estlett.1c00183.

[54] HM Government, Information on the Events Research Programme, Gov.Uk (2021).

[55] F. Adzic, B.M. Roberts, E.A. Hathway, R. Kaur Matharu, L. Ciric, O. Wild, M. Cook, L. Malki-Epshtein, A post-occupancy study of ventilation effectiveness from high-resolution CO2 monitoring at live theatre events to mitigate airborne transmission of SARS-CoV-2, Build Environ 223 (2022) 109392. https://doi.org/10.1016/J.BUILDENV.2022.109392.

[56] C. Iddon, B. Jones, F. Adzic, O. Wild, M.J. Cook, B.M. Roberts, L. Malki-Epshtein, Monitoring and modelling the impact of ventilation on the long range exposure risk to SARS-CoV-2 laden aerosols in restaurants, Preprint (2022). https://doi.org/https://dx.doi.org/10.2139/ssrn.4268501.

[57] B.M. Roberts, F. Adzic, E.A. Hathway, C. Iddon, B. Jones, M.J. Cook, L. Malki-Epshtein, Measurement of ventilation effectiveness and indoor air quality in toilets at mass gathering events, in: 43rd AIVC-11th TightVent & 9th Venitcool Conference, Copenhagen, Denmark, 2023: pp. 1–10.

[58] F. Adzic, O. Wild, C. Iddon, M. Cook, L. Malki-Epshtein, Evaluating ventilation of concession stands in large sports and entertainment venues using CO_2 monitoring, in: Proceedings of the 2024 CIBSE Technical Symposium, 2024.

[59] HM Government, Roadmap out of lockdown, (2021).

[60] UK Government, Information on the Events Research Programme, Online (2021). https://www.gov.uk/government/publications/information-on-the-events-research-programme/information-on-the-events-research-programme (accessed September 16, 2023).

[61] L. Malki-Epshtein, S. Gwynne, M. Cook, 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, Online (2021). https://www.gov.uk/government/publications/events-research-programme-phase-ii-and-iii-findings/science-note-emerging-findings-from-studies-of-indicators-of-sars-cov-2-transmission-risk-at-the-events-research-programme-environment-crowd-densi (accessed September 16, 2022).

[62] J.F. Brown, J.G. Smith, K. Tataris, Medical management of mass gatherings, Emergency Medical Services: Clinical Practice and Systems Oversight (2015) 264–271.

[63] S. Gwynne, A. Hunt, H. Xie, S. Owen, A. Hamilton-Smith, S. Hunt, Methodology developed for field observations of large events during the pandemic, Saf Sci 176 (2024) 106483.

[64] J.J. Fruin, Pedestrian planning and design, Metropolitan Association of Urban Designers and Environmental Planners, 1971.

[65] G.K. Still, Introduction to crowd science, CRC Press, 2014.

[66] A. Larsson, E. Ranudd, E. Ronchi, A. Hunt, S. Gwynne, The impact of crowd composition on egress performance, Fire Saf J 120 (2021) 103040.

[67] J.J. Rainey, D.B. Koch, Y.H. Chen, J. Yuan, A. Cheriyadat, Using video-analysis technology to estimate social mixing and simulate influenza transmission at a mass gathering, Epidemics 36 (2021). https://doi.org/10.1016/j.epidem.2021.100466.

[68] ASHRAE, ASHRAE Position Document on Indoor Carbon Dioxide, 2025.

[69] SAGE-EMG, Role of ventilation in controlling SARS-CoV-2 transmission, HM Government (2020). https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/928720/S0789_EMG_Role_of_Ventilation_in_Controlling_SARS-CoV-2_Transmission.pdf (accessed April 29, 2022).

[70] B. Jones, C. Iddon, M. Sherman, Quantifying quanta: Determining emission rates from clinical data, Indoor Environments 1 (2024) 100025. https://doi.org/10.1016/j.indenv.2024.100025.

[71] B. Jones, C. Iddon, M. Zaatari, P. Wargocki, R. Bruns, Risk modeling for ASHRAE Standard 241-2023–Control of infectious aerosols, Build Environ (2025) 113318. https://doi.org/https://doi.org/10.1016/j.buildenv.2025.113318.

[72] S. De-Ville, S. Pott, C. Wood, Z. Peng, M.Z. Farooq, G. Blouchou, A. Suhag, E. Murphy, E.A. Hathway, Improving hospitality venue ventilation via behavioural change as a response to the COVID-19 pandemic, Indoor Environments (2025) 100097.

[73] H. Shetabivash, Investigation of opening position and shape on the natural cross ventilation, Energy Build 93 (2015) 1–15. https://doi.org/10.1016/J.ENBUILD.2014.12.053.

[74] C.F. Gao, W.L. Lee, Evaluating the influence of openings configuration on natural ventilation performance of residential units in Hong Kong, Build Environ 46 (2011) 961–969. https://doi.org/10.1016/J.BUILDENV.2010.10.029.

[75] C.V.M. Vouriot, M. van Reeuwijk, H.C. Burridge, Robustness of point measurements of carbon dioxide concentration for the inference of ventilation rates in a wintertime classroom, Indoor Environments 1 (2024) 100004.

9 Appendix – Venue descriptions, images, and floorplans

9.1 Ascot Racecourse

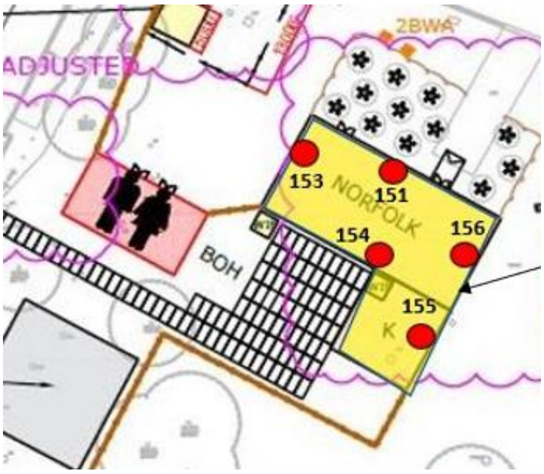


Figure 14: RA1 marquee at Ascot Racecourse. Red dots indicate the location of a CO_2 sensor.

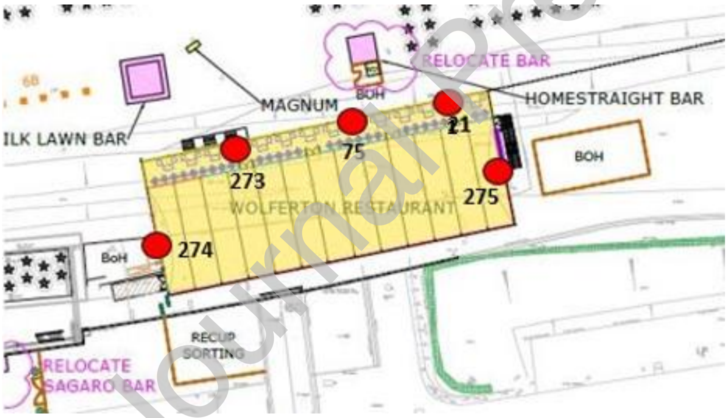


Figure 15: RA5 marquee at Ascot Racecourse. Red dots indicate the location of a CO_2 sensor.

9.2 Donington Park music festival

Table 4: Music festival event timings (setlist)

	Day 1		Day 2 and Day 3	
	Time (hh:mm)	**Duration (mins)**	**Time (hh:mm)**	**Duration (mins)**
Event 1	17:00 – 17:30	30	11:30 – 12:00	30
Interval 1	17:30 – 18:00	30	12:00 – 12:30	30
Event 2	18:00 – 18:35	35	12:30 – 13:00	30
Interval 2	18:35 – 19:20	45	13:00 – 13:30	30
Event 3	19:20 – 20:00	40	13:30 – 14:00	30
Interval 3	20:00 – 20:50	50	14:00 – 14:30	30
Event 4	20:50 – 21:50	60	14:30 – 15:00	30
Interval 4	-	-	15:00 – 15:35	35
Event 5	-	-	15:35 – 16:10	35
Interval 5	-	-	16:10 – 16:50	40
Event 6	-	-	16:50 – 17:30	40
Interval 6	-	-	17:30 – 18:15	45
Event 7	-	-	18:15 – 19:05	50
Interval 7	-	-	19:05 – 20:15	70
Event 8	-	-	20:15 – 21:25	70

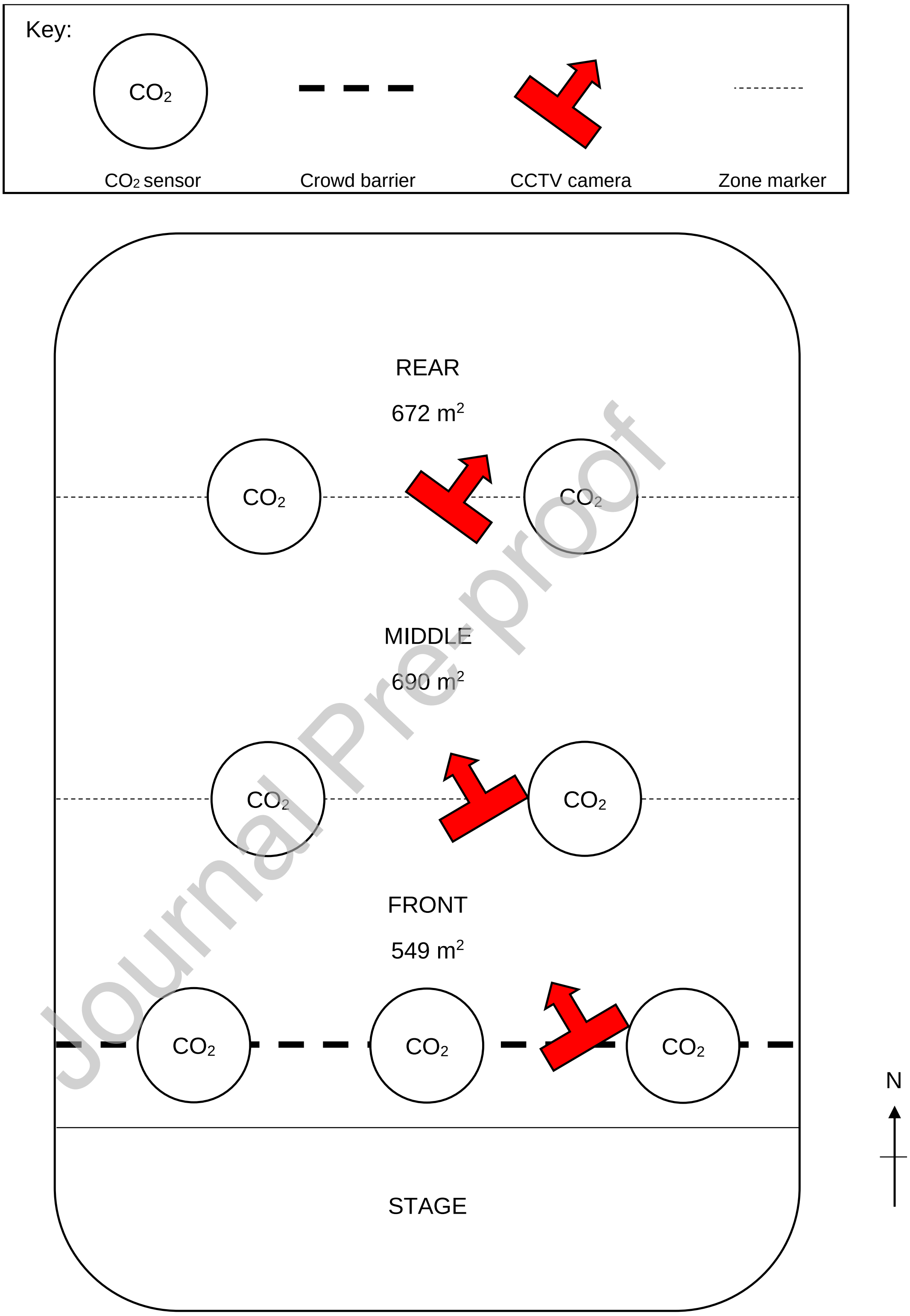


Figure 16: Floorplan, sensor locations, and video camera positions in the semi-outdoor music festival tent.

Figure 17: Video camera image and measurement square at the semi-outdoor music festival.

9.3 The Grange Theatre

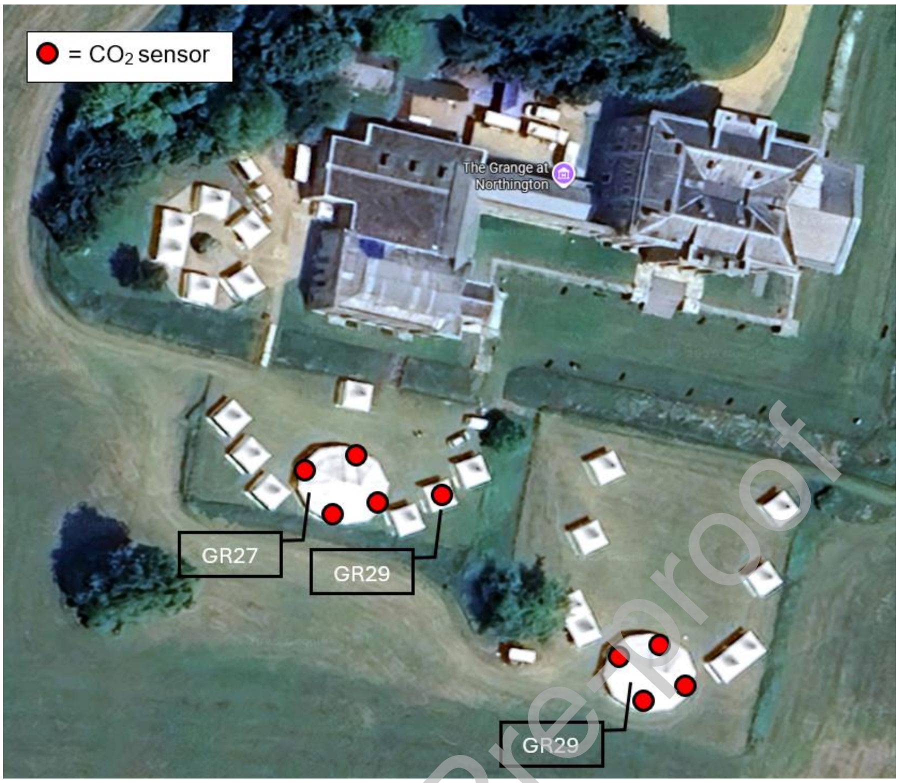


Figure 18: The Grange marquees with sensor locations marked

9.4 Graduation ceremony marquee

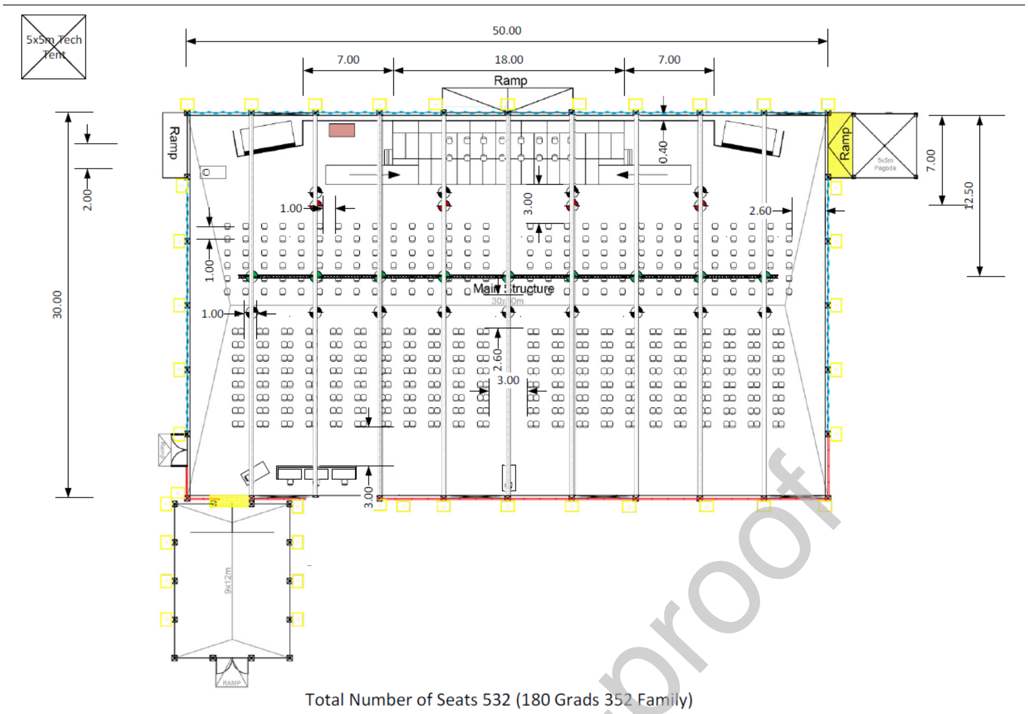
Table 5: Graduation ceremony timings

Ceremony number	Time (hh:mm)	Duration (mins)
Ceremony 1	09:55 – 10:40	45
Interval 1	10:40 – 11:35	55
Ceremony 2	11:35 – 12:20	45
Interval 2	12:20 – 13:30	70
Ceremony 3[a]	13:30 – 14:15	45
Interval 3	14:15 – 15:10	55
Ceremony 4	15:10 – 15:55	45
Interval 4	15:55 – 16:50	55
Ceremony 5[b]	16:50 – 17:35	45

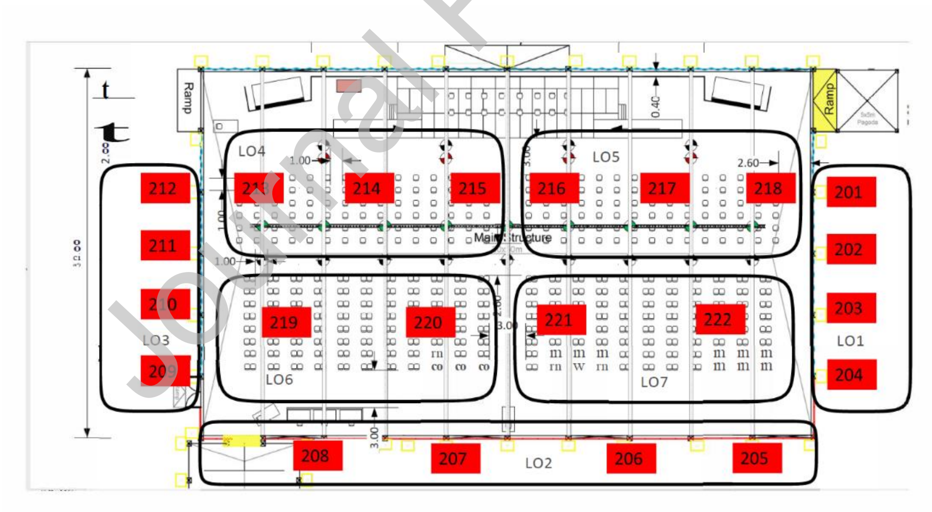
[a] On Thursday 22 July and Monday 26 July, there was no Ceremony 3.

[b] On Tuesday 20 July and Thursday 29 July, there was no Ceremony 5.

Figure 19: Photograph of the graduation marquee with open sides visible.



(a)



(b)

Figure 20: Floorplan and sensor locations in the graduation marquee.

9.5 The nightclub (indoor venue for comparison purposes)

The indoor nightclub is described in detail elsewhere [15].

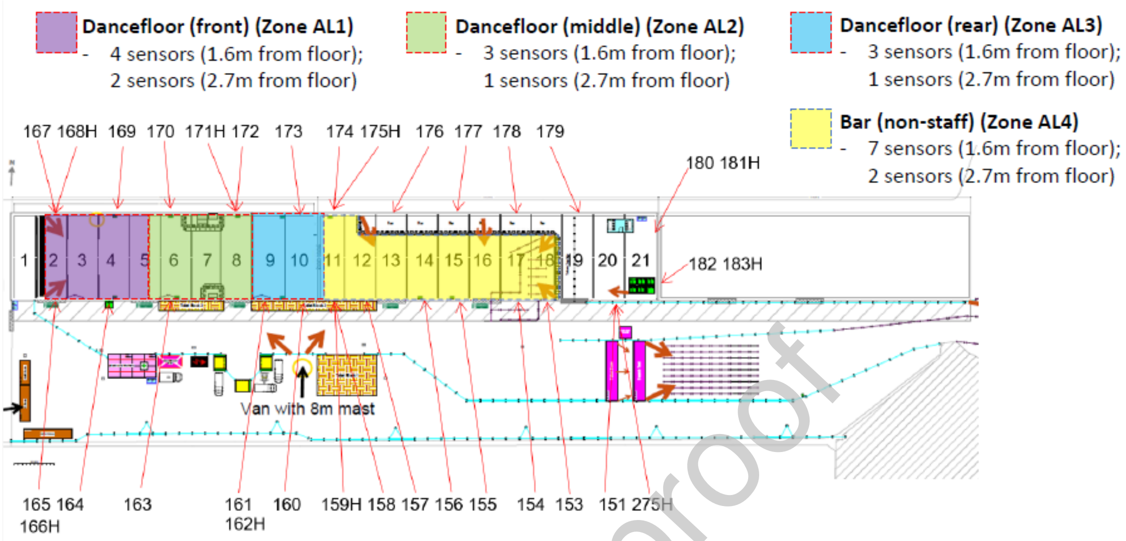


Figure 21: Floorplan and sensor locations in the indoor nightclub.

Table 6: Indoor nightclub setlist and timings on 30 April 2021

Act number	Time (hh:mm)	Duration (mins)
1	14:00-15:00	60
2	15:00-16:30	90
3	16:30-18:00	90
4	18:00-19:30	90
5	19:30-21:00	90
6	21:00-23:00	120

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: