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A post-occupancy study of ventilation effectiveness from high-resolution CO_2 monitoring at live theatre events to mitigate airborne transmission of SARS-CoV-2

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ABSTRACT

Mass-gathering events were closed around the world in 2020 to minimise the spread of the SARS-CoV-2 virus. Emerging research on the transmission of SARS-CoV-2 emphasised the importance of sufficient ventilation. This paper presents the results of an indoor air quality (IAQ) monitoring study over 82 events in seven mechanically ventilated auditoria to support the UK government Events Research Programme. Indoor carbon dioxide concentration was measured at high resolution before, during, and after occupancy to allow for assessment of the ventilation systems. Generally, good indoor air quality was measured in all auditoria, with average IAQ found to be excellent or very good for 70% of spaces. In some auditoria, spatial variation in IAQ was identified, indicating poor mixing of the air. In addition, surface and air samples were taken and analysed for the presence of bacteria by culture and SARS-CoV-2 using RT-qPCR in one venue. SARS-CoV-2 RNA was detected on a small number of surfaces at very low copy numbers, which are unlikely to pose an infection risk. Under the ventilation strategies and occupancy levels investigated, it is likely that most theatres pose a low risk of long-range transmission of COVID-19.

1. Introduction

In 2020, the rapid spread of Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) and the subsequent global pandemic of COVID-19 led to the suspension of mass-gathering events. In the UK, culture, sports, music, and entertainment venues were closed. In 2018 theatres in the UK employed 290,000 people with a generated ticket revenue of £1.28 billion. As tight lockdowns were introduced to curb the infection spread in early 2020, over 15,000 shows were cancelled in the first 12 weeks, causing a huge loss in box office revenues [1], and live events were not permitted for over a year.

Mass-gathering events including a beer festival in Germany (Brandl et al., 2020), a wedding in Jordan [2], a dinner dance in Spain (Domènech-Montoliu et al., 2021), and various religious festivals in Malta [3], Malaysia [4] and France [5] were associated with the transmission of SARS-CoV-2. Closure of all mass-gathering events was a critical pandemic mitigation measure during the early stages of pandemics before medical countermeasures were available [6].

Around the world, research programmes were initiated to examine the risks of reopening mass-gathering events. For example, in Barcelona, Spain, in December 2020, an indoor music concert was monitored via a randomised control trial involving screening of attendees with antigen-detecting rapid diagnostic tests and encouraging adequate ventilation [7]. In Leipzig, Germany, three simulated (staged) events took place in August 2020 in a multi-use arena to examine the number of close contacts between attendees, with subsequent Computational Fluid Dynamics (CFD) modelling further investigating the effect of different ventilation strategies on SARS-CoV-2 transmission [8]. The study concluded that, with adequate ventilation, mass-gathering events pose a low risk of the epidemic spread of COVID-19. However, a limitation of the work was that no measurements of indoor air quality (IAQ) were taken and instead the IAQ assessment was derived from the CFD model, which may contain uncertainties associated with modelling assumptions made. During this time evidence was emerging that the SARS-CoV-2

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virus was transmitted via airborne routes: aerosols and droplets [9], and so greater emphasis was being placed on ventilation provision in buildings to dilute and remove airborne viruses [10,11]. The measurement of indoor carbon dioxide (CO_2) concentration is important as it allows for comments to be made on ventilation provision in buildings and the associated risks of long-range airborne virus transmission since CO_2 can be used as a proxy for exhaled breath and exhaled breath may contain suspended aerosols containing viral particles [12].

High concentrations of CO_2 in an indoor space indicate low levels of ventilation, high occupancy relative to the space volume, or a combination of both, and high-resolution monitoring allows for a basic air quality classification to be made for rapid assessment of spaces [13]. Further and more detailed assessment of airborne virus transmission risk can then be made using more sophisticated models such as those developed by Jones et al. [14] and Peng et al., [15]. However, these models can only be applied in single-zone spaces that are well-mixed.

While CO_2 concentrations give an indicator of ventilation effectiveness and can be used in models that attempt to predict the risk of airborne transmission, it is notoriously difficult to identify specific transmission events and the great majority of studies do not include a microbiological assessment of the indoor spaces. Microbiological sampling of the air was carried out on healthcare premises and in clean rooms in some studies (y, Masotti et al., 2019), but there is little evidence from public spaces. Furthermore, there are no real standards that outline what an acceptable level of microbiological contamination is, in normal times or during a pandemic. The guidance for operating theatres states that bacterial colony counts (CFUs) per m^3 of air should be < 180 [16] and packing areas in pharmaceutical production premises should be < 200 CFU/m^3, [17]. The Ministry of the Environment in Singapore produced guidelines for the air quality of office spaces which state that bacterial counts should not exceed 500 CFU/m^3 [18].

Theatres are complex spaces to ventilate as the air distribution occurs over a large area, and they must be carefully designed because the ventilation system must be quiet so as not to audibly disturb the performance whilst coping with intermittent high heat loads associated with the occupancy and stage lighting [19]. Prior research on the indoor environmental quality of theatres has tended to focus on occupant thermal comfort e.g. Refs. [20–27], or operational energy reduction [28]. Airborne bacteria were sampled from the air in a lecture theatre in China, but the study investigated only one space for one day, so only preliminary conclusions could be drawn [29]. A theatre in Belgrade was able to maintain CO_2 concentration to below 1000 ppm during most of the performance, but it did so by over-ventilating the space and thus compromising thermal comfort and increasing energy demand [19].

The aim of the following study was to provide evidence for the UK government to assess the risk of reopening mass-gathering events in theatre auditoria with respect to long-range airborne transmission of SARS-CoV-2. In England, the UK Government initiated the Events Research Programme (ERP) which is, at the time of writing, the largest programme of its kind undertaken worldwide. The ERP explored how a range of non-pharmaceutical interventions might mitigate the spread of SARS-CoV-2 in a series of special pilot events across 31 venues between April and July 2021 [30]. The venues ranged from sports stadia to nightclubs [13]. Events were run at reduced capacity under special permissions [31]. A wide range of theatres was studied under the ERP to enable the Government to evaluate the UK theatre stock as a whole and determine how well theatres were likely to perform regarding ventilation and mitigation of airborne transmission. The selection was made based on willingness to participate in the ERP programme and on achieving a wide variety of theatre types in terms of architectural design, space volume, occupancy, and ventilation systems. This is the largest monitoring campaign of theatre auditoria in operation, to the authors' knowledge.

This study compares ventilation performance across seven theatres in England, of different ownership, space design, and ventilation schemes, operating within or shortly after the ERP. To achieve this, firstly indoor air quality at all theatres was monitored by measuring CO_2 concentration at high resolution, as a proxy for exposure to exhaled breath which had the potential to contain virus-laden aerosols, and as an indicator of the effectiveness of ventilation provision. Furthermore, a microbiological assessment of the air and surfaces was also conducted during one event and subsequently analysed for microbacterial contamination and the presence of the SARS-CoV-2 virus. Finally, an air quality analysis was carried out to assess the ventilation effectiveness at the venues during the events.

2. Methods

At the heart of a theatre is the auditorium; the main space occupied by people watching a theatre performance. In some theatre spaces, the audience seating may be tiered and rise higher than the stage. There are a variety of spaces which support the theatre auditorium: backstage areas for performers, ticketing areas, bars, restaurants, corridors, and toilets, but the present study focuses only on spaces within the theatre auditoria. All auditoria studied were indoors and were all mechanically ventilated. Although this study focused on CO_2 monitoring, other variables such as occupancy and event management and performance times were also of crucial importance. Microbiology data were also collected at one live event in the O2 Arena auditorium. A diagram outlining the field study process and data collection is given in Fig. 1.

Dry bulb temperature, relative humidity, and CO_2 concentration were measured in each theatre auditorium at 2-min intervals by deploying multiple Explore CO_2 Senseair non-dispersive infrared (NDIR) sensors (accuracy = ± 30 ppm ± 3%; range 400–5000 ppm) [13] (Table 1). The logged data were accessed on an online database and also viewed in real-time on a dashboard. The number of sensors was installed as appropriate to each venue and in consideration of the geometry of the venue spaces and restrictions on fixing locations. The majority of the sensors in this study were installed on the back of or under seats, within the breathing zone of the occupants. The placement of sensors under seats enabled measuring at higher resolution in the auditoria. Several auditoria had under-seat ventilation system components or inlets, and these were avoided when CO_2 sensors were installed. The monitored auditoria were divided into zones. Each zone had at least two CO_2 sensors and comprised either of a block of seats or several rows grouped (Table 1).

2.1. Venues

Seven auditoria, all based in England, were monitored and presented in this study (Table 1). Theatre venues varied from historic buildings more than 100 years old (The Piccadilly, Lyceum and Grange theatres), to more modern constructions built in the last 50 years (The Crucible – 1970s, the Playhouse 1990s, the [32]; and the Liverpool Arena and Conference Centre (ACC) (2008). During the Event Research Programme, attendance was controlled due to COVID-19 regulations, and a range of occupancies was tested at different events at each theatre.[1] As described above, the auditoria were split into separate monitoring zones. In total 68 zones were monitored within 7 auditoria over 82 events with 9–50 sensors in each auditorium. An overview of the venues and events monitored is summarised in Table 1. The volume of each auditorium was estimated from drawings provided to the authors by building and event managers.

The Crucible Theatre in Sheffield hosts regular theatrical productions as well as the annual World Snooker Championship which was monitored in this study. The Crucible ventilation system consists of 34 diffusers which provide 210–412 l/s each. Fans were running at 50% for occupancies up to 50% and at 100% for occupancies of 75–100% full

[1] The Lyceum theatre was monitored outside the ERP but during a time when pandemic occupancy restrictions were still in place.

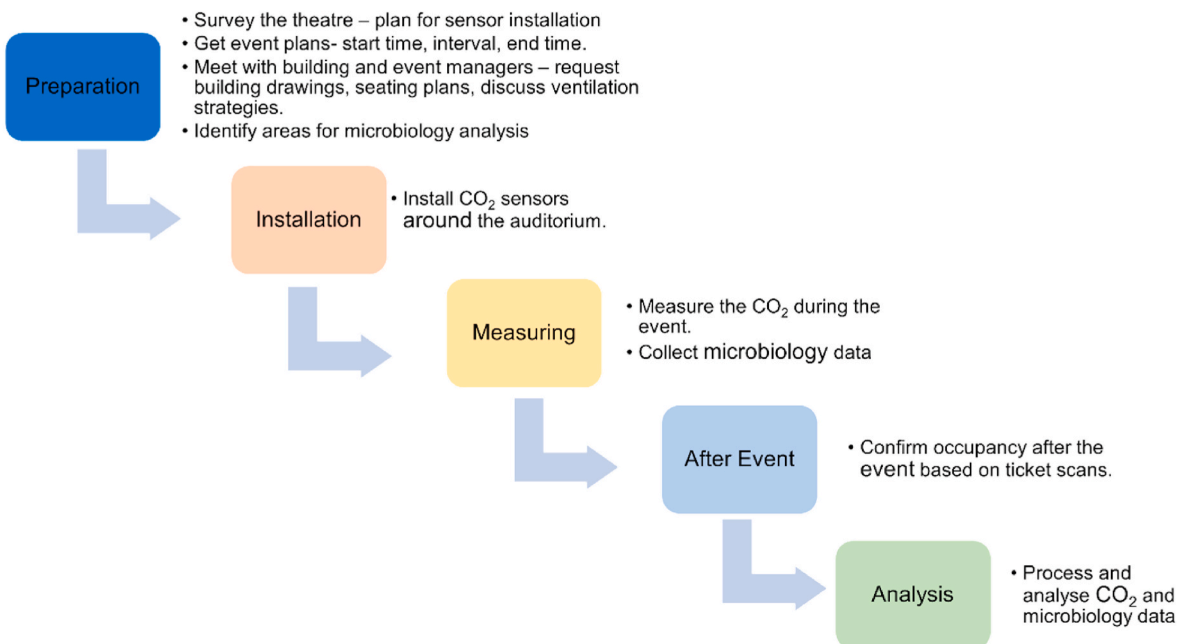

Fig. 1. Diagram of field study methodology.

Table 1
Name and location of theatre, description, date range, number of events, number of zones analysed, number of sensors deployed, auditorium volume in m^3, number of attendees, and the percentage of attendees relative to the total capacity.

Theatre	Event	Date of events	No. of events	No. of Zones	No. of Sensors	Auditorium volume (m^3)	No. of Attendees (Range)	% Capacity in use
Crucible Theatre, Sheffield	World Snooker Championships	17/04/21–03/05/21	46	5	50	4433	79–862	8–88
Lyceum Theatre	Musicals	10/11/21–25/11/21	12	14	32	9465	117–1003	11–94
Leeds Playhouse Theatre, Leeds	"A Little Night Music"	14/07/21–17/07/21	6	5	20	1529	205–262	18–24
Piccadilly Theatre	"Comedy Nights"	17/07/21–23/07/21	3	18	34	5040	227–603	18–49
The Grange, Northington	The Grange Opera Festival	02/07/21–18/07/21	12	15	28	3006	201–596	30–90
O2 Arena, London	"The BRIT Awards"	11/05/21	1	10	30	53,617	3532	18
ACC, Liverpool Main auditorium	"Good Business" Networking Event	28/04/21	1	1	18	21,235	191	22
ACC, Liverpool Left drum auditorium	"Good Business" Networking Event	28/04/21	1	1	9	5582	191	76

capacity. When fans are set to 50%, the system automatically ramps up when CO_2 measured in the extract duct reaches 650 ppm. The inlet damper was set to 100% open; this was increased from 50% open in pre-pandemic days. There are three ventilation inlets at the seating circumference and extracts at either side of the stage. The Crucible auditorium plan is shown in Figure A.1 (Appendix A) and it shows that the seating area follows the shape of a crucible, after which the theatre was named, with a thrust stage.

The Lyceum Theatre is also located in Sheffield, in a historic building repurposed for theatrical performances such as plays, musicals and dance, which additionally hosts a variety of other productions. The ventilation system was described to have an inlet at a high level in front of the auditorium, extracted from each level at the back of seating areas, with extracts provided on each of the three levels: Stalls, Circle and Balcony as shown in Figure A.2. (Appendix A). The Lyceum has a typical proscenium stage seating.

The Leeds Playhouse is a theatre located in Leeds city centre; a purpose-built, modern theatre with two separate stage rooms. For the purposes of this study, only the Quarry theatre, the larger of the two was monitored. The ventilation system was also described to have inlets at a high level. The inlets point towards the back of the auditorium. Air is extracted below the seats at the front. The seating is similar to the crucible, with sloping seats circling the main stage as shown in Figure A.3 (Appendix A).

The Piccadilly Theatre is located in London's West End and is a historical building used mainly for theatrical performances such as plays and musicals. In Piccadilly Theatre, the outside fresh air was supplied through two main air handling units (AHU) capable of providing a combined fixed airflow rate of 10.5 m^3/s. When the theatre is fully occupied, this fresh air flow rate would equate to 8.5 l/s per person. The seating is arranged in three levels: Stalls, Royal Circle and Grand Circle (Figure A.4, Appendix A) and it has a typical proscenium stage seating. In the theatre, the fresh air is supplied through the ceilings of the stalls, grand and royal circles, and auditorium dome, while the air is extracted from low-level extract terminals located in the stalls and above the stage.

Grange Opera House is a theatre located in a historical building in Hampshire that is mainly used for opera performances. In The Grange Opera House, the air is supplied via two main air handling units. The supplied air is then routed through the plenum and introduced into the space by under-seat supply terminals. The supply terminals are rectangular and located along the entire length of the rows as a single continuous opening. They are positioned in every other row. The suppled air then is driven by the buoyancy forces generated by the occupants and extracted at ceiling level by three non-mechanically operated extract stacks above the stage. The seating is arranged in three levels: Stalls, Lower Circle and Balcony (Figure A.5, Appendix A).

The O2 Arena is located in London and is a large, multi-purpose indoor arena used for events such as concerts, sports and awards ceremonies with a capacity of 20,000 spectators (Figure A.6, Appendix A). Outdoor air is brought in at ground level and rises into the roof before being distributed throughout the auditorium, with stale air exhausted through the auditorium roof via four extractor fans. For the event monitored, the ground level of the auditorium consisted of the stage and podium, with award recipient seating. The public was mainly seated on level 1 of the auditorium and level 2 consisted of private suites. Private suites also make up part of the auditorium as they are open spaces with balconies facing the central part of the auditorium. Apart from seating blocks on level 1, where the majority of the audience was placed for this event, lounges and terraces were also considered to be part of the main auditorium. In the O2 Arena, the lounges and terraces are placed just behind the main seating blocks, and they are slightly more private spaces with available bar and table service. Private suites from level 2, lounges, terraces, and seating blocks were included in both the indoor air quality and microbiology analysis. Microbiology data were analysed in the O2 Arena and not considered for other venues and events.

The ACC in Liverpool is a multipurpose arena and convention centre. It is adaptable which allows for the main auditorium to be partitioned into three smaller auditoria using rotating drums (Figure A.7, Appendix A). During the monitored event, the auditorium was fully partitioned, with the main auditorium and the left drum auditorium being occupied during the event, with a capacity of 1350 in total (850 main auditorium capacity, 250 each drum capacity). All auditoria in the ACC were mechanically ventilated with an underfloor fresh air supply and extracted at ceiling level above the stage lighting gantries. The facilities manager reported that the ventilation system was designed to supply 12 l/s/person to both the main and drum auditoria.

2.2. Air quality classification

CO_2 values of 800–1000 ppm are used in many countries as an appropriate target for ventilation rates. In the UK, pandemic guidance from The Scientific Advisory Group for Emergencies for the UK government (SAGE-EMG) recommended that spaces frequently reaching CO_2 levels above 1500 ppm should be improved [33]. Moreover, CIBSE Guide A [34] provides a range of 5–10 l/s/person of outdoor air. The range comes from studies on occupant comfort and air “stuffiness”. A flow rate of 10 l/s/person is considered to provide a high comfort level and result in sustainable energy usage.

An international standard on energy-efficient delivery of occupant comfort, BSEN16798 [35], provided four levels of IAQ levels of expectation based on occupancy (Table 2). The categories were based on occupants’ expectations. A normal expectation level for office space would be “Medium”. A higher expectation level may be selected for occupants with special needs (children, elderly, persons with disabilities, etc.). A lower expectation level will not provide any health risk but may decrease comfort and satisfaction with the space, or increase energy use. Interestingly this standard is most likely referring to the psychological discomfort of exposure to general effluents from occupants, rather than the emission of pathogens from occupants, and does not consider the risk of exposure to indoor air pollutants emitted from building materials and furnishings, or to the increased risk of exposure to pathogens such as viruses and bacteria [13].

Table 2
Recommended targets for CO_2 levels for Indoor Air Quality, adapted fromBSEN16798 [35].

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

Based on the BSEN16798 [35], SAGE [33] and CIBSE Guide A [34] guidelines, Table 3 presents the classifications developed for this study as described in Ref. [13]. To allow detailed analysis of different types of spaces used for different purposes, the IAQ classification bands were proposed to range from A to G: A being the outdoor air equivalent, B presenting very good air quality, C D and E corresponding to medium air quality for different circumstances and F and G, with CO_2 concentrations above 1500 ppm, indicating concerning low ventilation rates that should be prioritised for improvement. For this theatre auditoria study, it was assumed that outdoor values of CO_2 are 400 ppm and CO_2 above the baseline value are derived from human exhalation.

For each zone and each event, maximum CO_2 values were identified as the maximum concentration in the space for the duration of an event. Average CO_2 values were calculated as the average of all sensors in each space, averaged in time during an entire event. These average and maximum values were used to classify each space according to Table 3. Event duration was defined as the time in which the venue was occupied by spectators, and for theatre auditoria, that was usually for the duration of the show including the programmed interval (mid-performance break) time. Researchers were present for the majority of the events monitored in this study and noted important times during the events. Researcher observations closely matched the event plans provided by event managers. Thus, defining averaging times for analysis was straightforward. The averages would start 15–30 min before the event start to 15–30 min after the event is over, depending on the structure of the event. The averages include the intervals.

2.3. Microbiology methods

A total of 47 surface samples were collected during the course of one

Table 3
Classification for Air Quality bands A to G and their corresponding CO_2 concentrations (absolute values in ppm; excess concentration above outdoor values of 400 ppm) developed for the Events Research Programme by Malki-Epshtein et al. [13],

Air Quality Bands	Classification	Range of CO_2 concentrations – Absolute Values (ppm)	Range of excess CO_2 concentrations – Above outdoor (ppm)
At or marginally above outdoor levels	A	400–600	0–200
Target for enhanced aerosol generation (singing, aerobic activity)	B	600–800	200–400
High air quality design standards for offices	C	800–1000	400–600
Medium air quality	D	1000–1200	600–800
Design standards for most schools pre-Covid	E	1200–1500	800–1100
Priority for improvement [33]	F	1500–2000	1100–1600
Low ventilation/ dense occupancy. Must be improved	G	>2000	>1600

live event held at the O2 Arena in areas used by spectators. These consisted of the general gate areas where spectators arrived, the spectator seating blocks in the main arena, spectator terraces with tables in the main arena, and more private and enclosed spectator lounge areas (approx. 50 spectators) where food and drinks were served; and enclosed suites for private parties (approx. 20 spectators) which had their own food served and a bar. Both the lounges and the suites opened up onto the main auditorium. A total of six air samples were collected in the gate, lounges, and suites at times when these areas were at maximum occupancy.

Surface samples were taken from high-touch surfaces (e.g., door handles/push plates, counters, tables) within the venue using sterile cotton swabs and stored in molecular-grade water. The air in these areas was also sampled using a Coriolis micro air sampler into 10 mL of molecular grade water with a flow rate of 300 L/min (for a total of 3000 L). Samples were stored at 4 °C overnight and analysed for the presence of bacteria by culture on Tryptone Soya Agar for 48 h at 37 °C. Data was collected by counting bacterial forming units after incubation.

All samples were analysed for the presence of SARS-CoV-2 RNA using RT-qPCR based on the methods of Brown et al., [36]. The SARS-CoV-2 N gene using a Taqman assay. Thermal cycling conditions an RT step of 50 °C for 10 min and 95 °C for 2 min, followed by 45 cycles of 95 °C for 5 s and 60 °C for 20 s. The master mix used was the Inhibitor-tolerant RT-qPCR mix (Meridian). Prior to RT-qPCR, the samples were heated to 95 °C for 10 min to disrupt the viral envelope and release RNA. All samples were run in duplicate. Control SARS-CoV-2 nucleic acid was used as a positive control and to create a standard curve as described in Brown et al., [36].

3. Results

3.1. CO_2 time-series during events

Time-series of all the auditoria included in this study were plotted for events of highest occupancy. Apart from the spatial average and maximum CO_2, the plots also show how well-mixed the auditoria are, as all zones within the auditoria are included. All plots show event start and event end times, as well as temporal average periods, shown as shaded rectangles. If the event included an interval, it was also marked on the graphs.

Overall, 46 events were monitored in the Crucible. The last event day was plotted in Fig. 2 with two events on the day pictured. Attendance was at 88% full capacity. The average CO_2 at the 19:00 event was 1069 ppm and the maximum was 1480 ppm. The plot indicates that demand-controlled ventilation increases after the average CO_2 peaks above 1000 ppm, resulting in a slow decrease in measured levels.

Overall, 12 events were monitored in the Lyceum theatre and the highest occupancy event of 94% capacity was plotted in Fig. 3. The mean CO_2 during the event was 1211 ppm and the maximum was 1617 ppm. The interval resulted in some people leaving the auditorium and the CO_2 levels dropping for the interval duration. It can be noted that the highest values were recorded in the circle seating area, and Stalls and Balcony have similar levels.

In total, 6 events were monitored in Leeds Playhouse, all having similar occupancy. The event day plotted in Fig. 4 had the highest recorded occupancy. Attendance was at 24% of full capacity. The average CO_2 at the 19:00 event was 516 ppm, and the maximum was 618 ppm. The plot shows that CO_2 levels remain steady, with a slight drop during the interval in the middle of the performance.

Piccadilly theatre hosted three events during the Events Research Programme with varying occupancies. The event on 20 July had the highest occupancy (49% of full capacity). There was no interval during this performance. It cannot be assumed that all sections of the theatre were equally busy as the occupancy was quite low. The Grand Circle (upper tier) had a lower CO_2 value than the Royal Circle (middle tier) and the Stalls sections.

A total of 12 events were monitored in Th Grange Opera House with varying occupancy. The event with the highest attendance of 90% full capacity is given in Fig. 6. Because of the number of occupants, it is assumed that all sectors of the theatre have a similar number of spectators. The mean CO_2 during the event was 574 ppm and the maximum was 1410 ppm. The event average is much lower than the mean due to the nature of the events run at The Grange Opera House, which includes a 100-min interval. During the interval, the spectators left the auditorium and moved to the dining and outside areas. It can be noted that the highest values were recorded in the Balcony seating area, with Circle closely following Balcony readings. Stalls had much lower CO_2 concentrations.

The Brit Awards event in the O2 Arena was run at a significantly reduced capacity with 3532 attendees, which is around 18% capacity. Only this one event was monitored in the O2 Arena so the occupancy variation effects on CO_2 were not examined. Three blocks of occupied seats in the arena were plotted, showing no sharp peaks in CO_2 levels (Fig. 7). The average CO_2 for this event was 620 ppm and the maximum was 750 ppm. The Brit Awards event did not have typical theatre performance intervals, but there were many short breaks during the event and the audience was frequently visiting the concession units outside the auditorium.

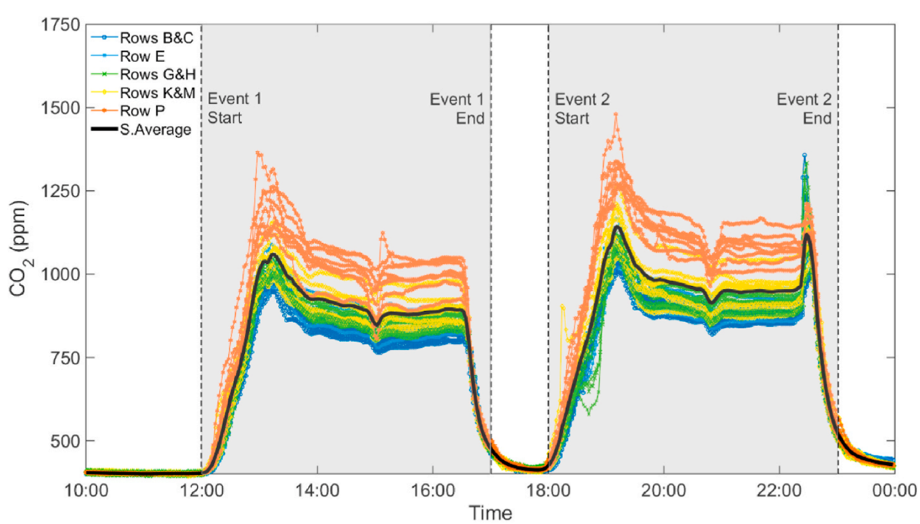

Fig. 2. Crucible world snooker championship – events on May 03, 2021.

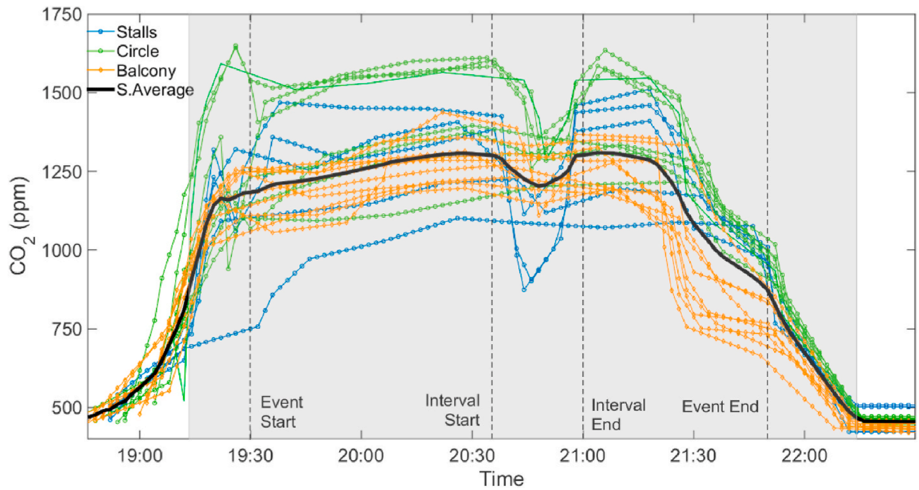

Fig. 3. Lyceum theatre- event on November 20, 2021.

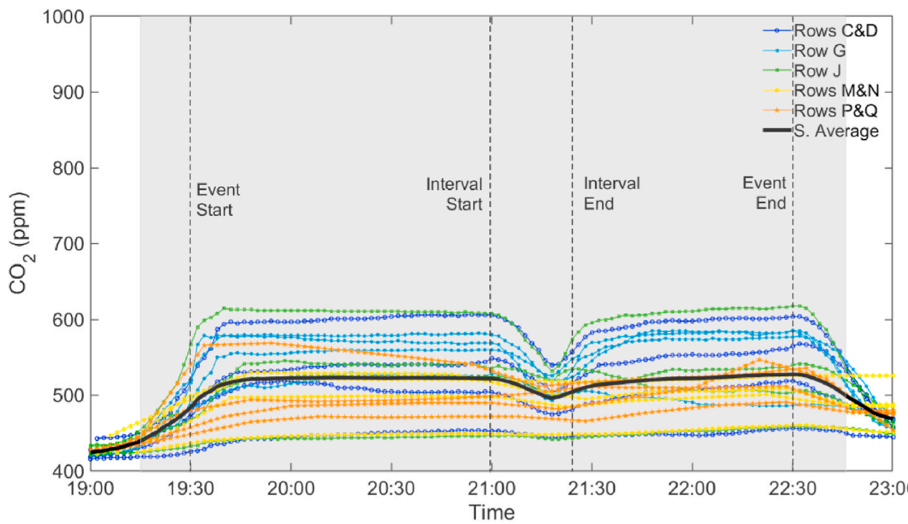

Fig. 4. Leeds playhouse - event on July 17, 2021.

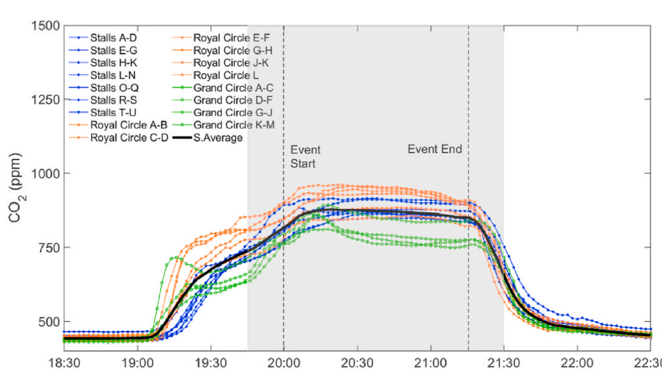

Fig. 5. Piccadilly Theatre event on July 20, 2021 (highest occupancy event).

Two consecutive periods of occupancy at the ACC were observed. The first was in the main auditorium (Fig. 8a) and the second in the smaller drum auditorium (Fig. 8b) on the same day. The occupancy for both events was similar, with around 191 attendees (around 22% and 76% of full capacity in the main and drum auditorium respectively). The average and maximum CO_2 in the main auditorium were 527 and 593 ppm respectively, and the CO_2 in the drum auditorium were 512 and 750 ppm respectively.

3.2. Overall air quality

To obtain a picture of the quality of ventilation provision for events and theatres, the ventilation performance was determined for each and every space and then aggregated. For every space, average performance was determined based on the mean (spatial and temporal average) CO_2 values, with an understanding that this represents performance under various occupancy scenarios. (Fig. 9a). Moreover, the maximum CO_2 value obtained for all events was also found, to identify the worst (maximum) performance for each space (Fig. 9b). Maximum CO_2 values were found in spaces for events with the highest occupancy. The spaces were then classified into air quality bands following Table 3.

The average air quality was in Band A or B for around 70% of the spaces monitored across the events (Fig. 9). The majority of the spaces were placed in Band B. A considerable number of spaces were in Band C, which is the equivalent to air quality standards in offices. Classification based on maximum CO_2 varied. Only 22% of the spaces were classified as Band A or B, and 41% of the spaces across all the events were classified as Band C or D having medium air quality. Furthermore, 37% of the spaces were in Band E and F at peak occupancies.

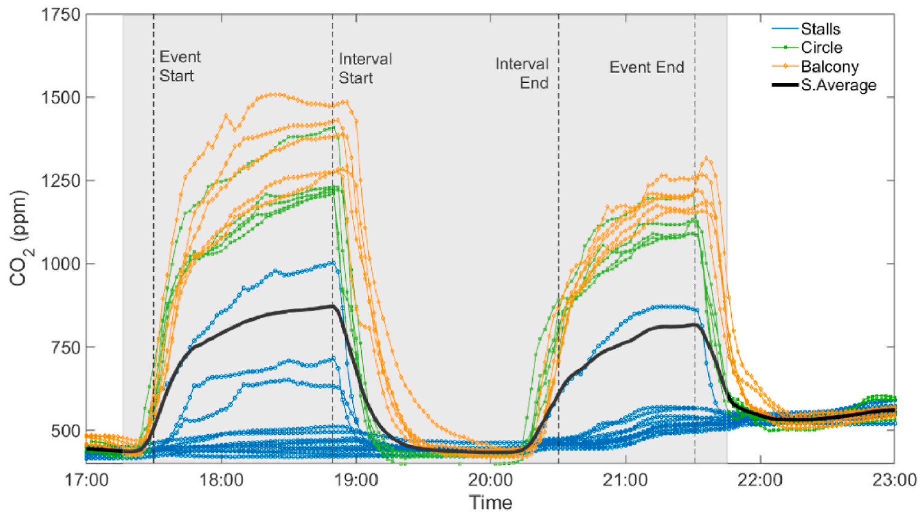

Fig. 6. Grange opera-event on the July 16, 2021.

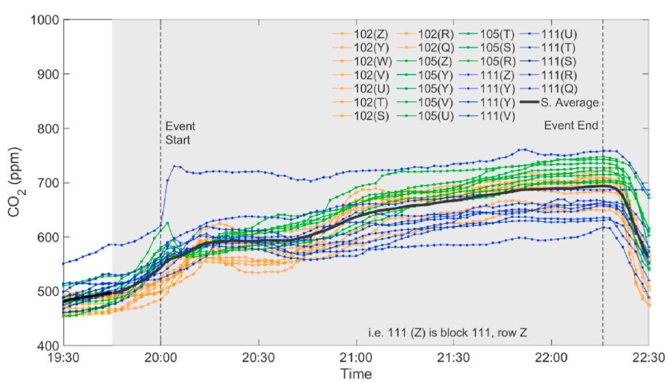

Fig. 7. O2 arena, brit awards on May 11, 2021.

3.3. Ventilation rates and impact of theatre size

For each auditorium, data from the highest occupancy event is summarised in Table 4, which presents: average and maximum CO_2 levels for that event and their respective classifications based on Table 3, average and maximum standard deviation values, and estimated overall ventilation rate. The average and maximum standard deviations refer to the distribution in individual sensor CO_2 readings around the auditorium, compared to the spatial average or absolute maximum CO_2 values. The results demonstrate how well the air in the auditoria was mixed and whether some parts of the auditoria presented with significantly higher readings than others.

From Table 4, it can be noted that the largest standard deviation was in the Grange Theatre, showing that the air in the Balcony area is not mixing well with the air in the Stalls. A similar observation can be made for the Lyceum theatre in which the Stalls area presents with much higher CO_2 than the rest of the auditorium. Furthermore, the data show that air is not well mixed in the sloped seating arrangement at the Crucible auditorium. In this case, the further away the seats are from the stage, the higher the CO_2 values. The ACC main auditorium, Leeds Playhouse, and the O2 Arena indicate the air is quite well-mixed around the space with low standard deviations for the monitored occupancies. However, the ACC drum auditorium and the Piccadilly theatre auditorium show slightly elevated standard deviations. This could be because more people are seated in a particular area and not due to poor mixing of the space.

Ventilation rates were estimated in air changes per hour (ACH) from the spatial CO_2 average using the method outlined by Roulet & Foradini [37]. These ventilation rate estimates are only provided as general guides to the overall performance of the space because a number of the assumptions made around the homogenous distribution of the tracer gas, in this case, CO_2, in the space are not valid in large auditoria, as is evident from the CO_2 data presented above. Furthermore, it is assumed that there is no source of CO_2 during the period for the calculations of the decay, but it could not be guaranteed that the auditoria were fully vacated.

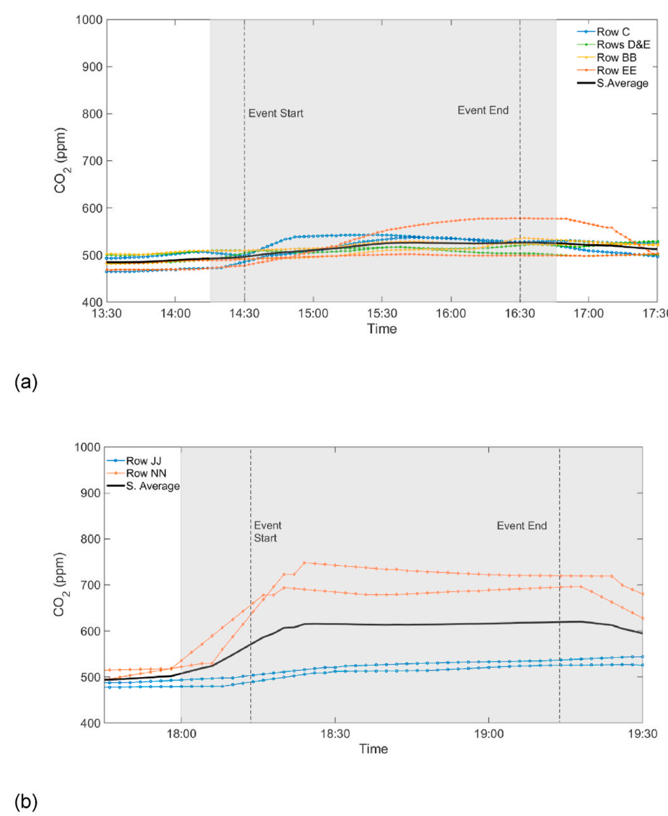

Fig. 8. (a) ACC main auditorium; (b) ACC drum auditorium – events on April 28, 2021.

It is evident from the results above that occupancy has an impact on CO_2 distribution throughout the auditoria. The impact of total occupancy on average and maximum CO2 is explored in three theatres that

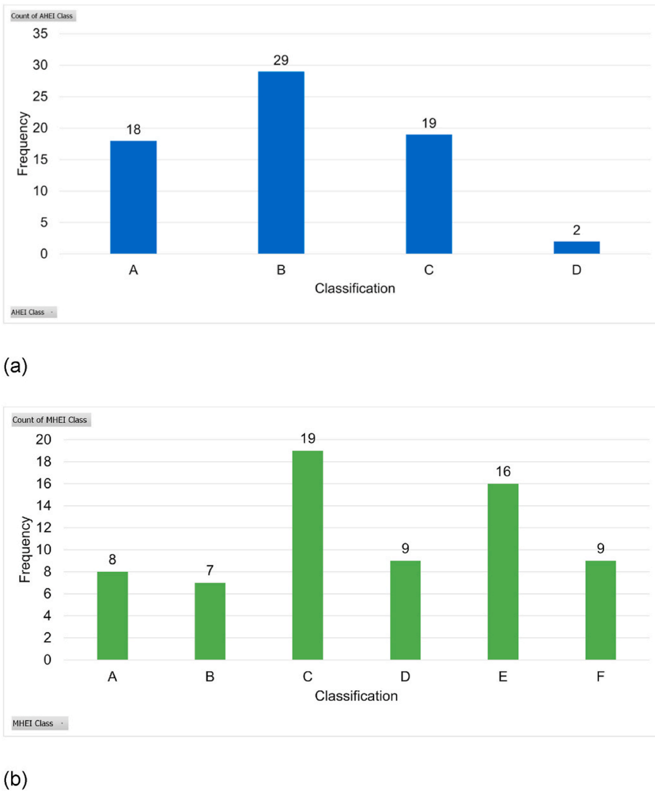

Fig. 9. (a) Average and (b) maximum CO_2 classification counts across all the events for all the auditorium zones monitored.

had multiple events, with a range of different occupancies.

In the Lyceum theatre, 12 events were monitored with varying occupancy (Fig. 10). CO_2 average and CO_2 maximum were calculated across all zones monitored in the auditorium for events. The full capacity of Lyceum Theatre is 1068 and the occupancy varied from around 10% to almost 100% capacity. Both average and maximum values show increases with rising occupancy.

The occupancy ranged from around 30% to above 90% In The Grange Opera events. CO_2 average and CO_2 maximum were taken across all zones monitored in the auditorium for events. The full capacity of the Grange auditorium is 660 people. Due to the nature of events run in The Grange Opera House, which includes a 100-min interval, the average CO_2 throughout the event, remains constant regardless of the increased occupancy (Fig. 11). However, increasing occupancy and maximum CO_2 readings during the event are correlated.

CO_2 averages and CO_2 maximums were taken across all zones monitored in the Crucible theatre auditorium (Fig. 12). The occupancy ranged from around 8%–88%. The full capacity of the Crucible auditorium is 980 people. The graph indicates both average and maximum values rising with the increased occupancy.

As seen from Figs. 10–12, maximum CO_2 values in the auditoria, over the averaged periods, were always found in those events with the highest occupancies.

The volume of air per person was calculated from the volume in the auditoria and the number of occupants at an event (Table 1). Average CO_2 values were calculated as the average of all sensors in each space, averaged in time during an entire event, with the averaging period of 15 min before the event started to 15 min after the event started as mentioned above. Fig. 12 shows 76 events, across different theatres, with varying occupancies. Fig. 13 correlates the volume per person provided by each event with the average CO_2 value at that event. It can be seen that the average CO_2 levels of an auditorium increase significantly when the total volume of air per person at an event is below 10 m3/person.

3.4. Microbiological sampling

Bacterial counts in the air were in a consistent range across different arena area types (Fig. 14). The numbers ranged from 2500 CFU/m^3 in the lounge areas to 5000 CFU/m^3 in the suites. No SARS-CoV-2 RNA was detected in any of the seven air samples. CO_2 presented in Fig. 14 is averaged at locations where air samples were taken, for 10 min to match the air sample measuring time.

Bacterial surface contamination in different areas varied (Fig. 15). The most highly contaminated surfaces were located in the terrace, lounge and suite areas, with mean viable bacterial counts of 1410, 2097 and 348 CFU/100 cm^2. The mean counts for gate and blocks were 60 and 86 CFU/100 cm^2 respectively.

The data is also examined according to surface type (Fig. 16). Surfaces were split into handles (e.g. door handles, bannisters, escalator handrail), service counters where food and drink were served, and table-tops where food and drinks were consumed. Service counters (mean 668 CFU/100 cm^2) and table-tops (656 CFU/100 cm^2) were more highly contaminated than handles (mean 186 CFU/100 cm^2).

SARS-CoV-2 N gene RNA was detected at low levels on 8.5% of all surfaces sampled, a total of 4 surfaces. Three of the four positive samples were located in two of the private suites and one in a lounge. The RNA

Table 4
Mean and maximum CO_2 concentrations with classifications from Table 3; Standard deviation in CO_2 readings in monitored auditoria on the event day with the highest occupancy and the estimated ventilation rate.

Auditorium	Event	Average CO_2 (ppm) & Classification	Maximum CO_2 (ppm) & Classification	Average Standard Deviation (ppm)	Maximum Standard Deviation (ppm)	Estimated Ventilation Rate (ACH)
Crucible	03/05/21	1069 (D)	1480 (E)	98	127	2.9
Lyceum	20/11/21	1211 (D)	1617 (F)	142	221	4.1
Leeds Playhouse	17/07/21	516 (A)	618 (B)	41	53	1.7
Piccadilly	20/07/21	680 (B)	1066 (D)	38	87	2.7
Grange	16/07/21	574 (A)	1410 (E)	167	418	3.8
O2 Arena	05/11/21	620 (B)	750 (B)	34	59	4.7
ACC (Main)	28/04/21	527 (A)	593 (A)	17	25	-[a]
ACC (Drum)	28/04/21	512 (A)	750 (B)	57	123	2.3

[a] A suitable CO_2 decay could not be found.

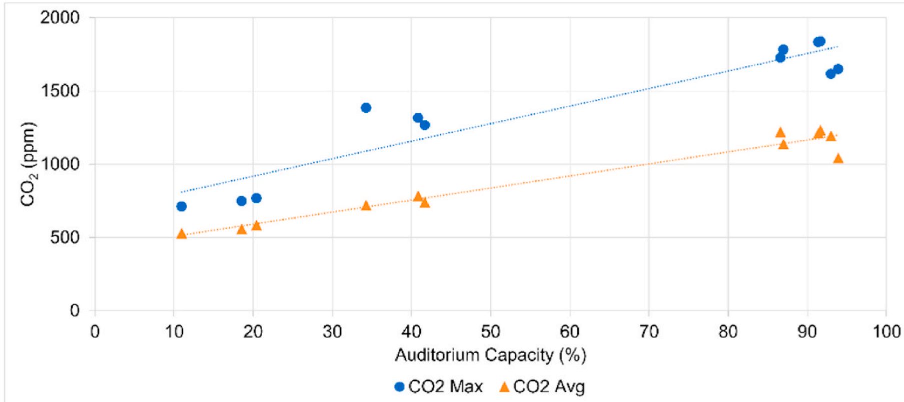

Fig. 10. Effect of varying occupancy in the Lyceum theatre on average and maximum CO_2.

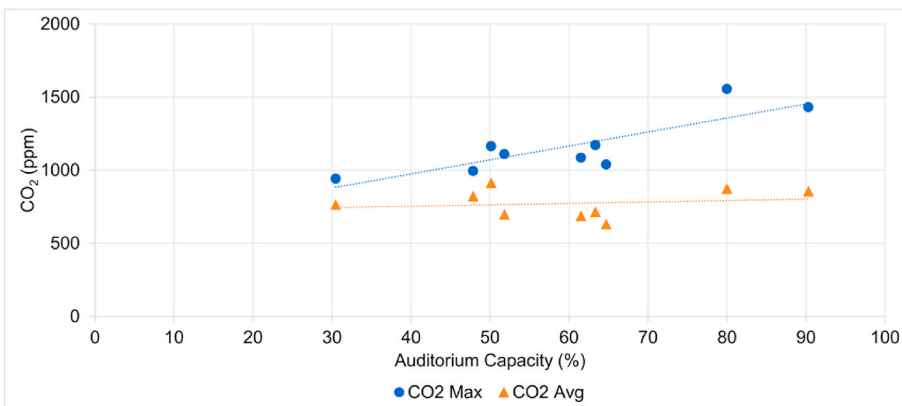

Fig. 11. Effect of varying occupancy in the Grange Opera on average and maximum CO_2.

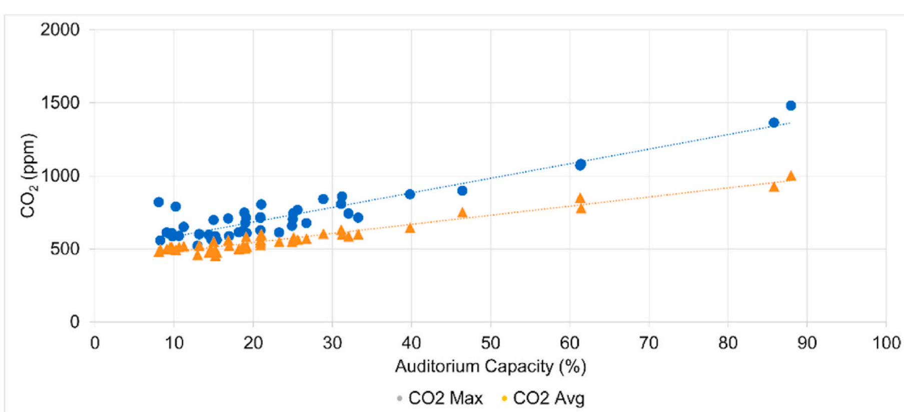

Fig. 12. Effect of varying occupancy in the Crucible on average and maximum CO_2 over 46 events.

copy numbers were very low ranging from 2.72 to 19.61 copies per 100 cm^2.

4. Discussion

4.1. Ventilation effectiveness

Deploying high-resolution CO_2 monitoring methodology, instead of a lower number of sensors, allows for detailed observations of CO_2 concentrations in multiple parts of the auditoria (zones). The data collected through high-resolution CO_2 monitoring in theatres shows that air was not well-mixed in the majority of auditoria monitored.

For example, in the Crucible Theatre (Fig. 2), CO_2 concentrations varied by nearly 400 ppm between the front and back rows of the auditorium. Audience members sitting in the back row were exposed to peaks of 1400 ppm in high occupancy events, whereas those in the front row generally breathed air comprising 800–950 ppm of CO_2. Some spatial variation in CO_2, although considerably lower, was seen in the ACC drum auditorium (Fig. 8b), in which the rear rows, which were elevated, had higher CO_2 concentrations. The Crucible and the ACC drum auditorium are single-level auditoria with sloping seats, rising from the stage upwards.

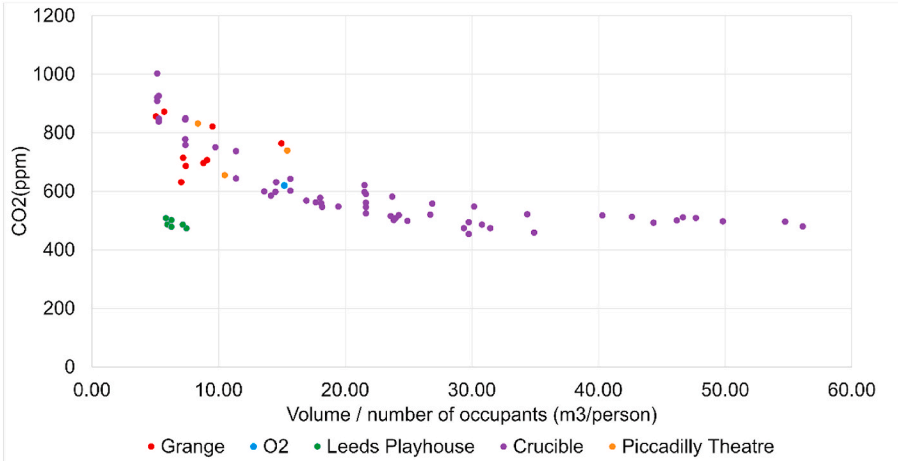

Fig. 13. Event average CO2 as a function of the volume of air per person (m^3/person).

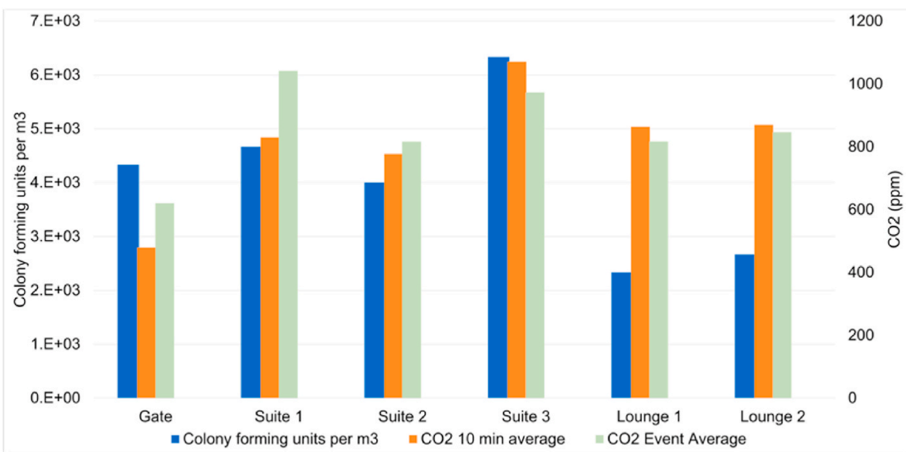

Fig. 14. Bacterial colony-forming unit counts in the air of different areas.

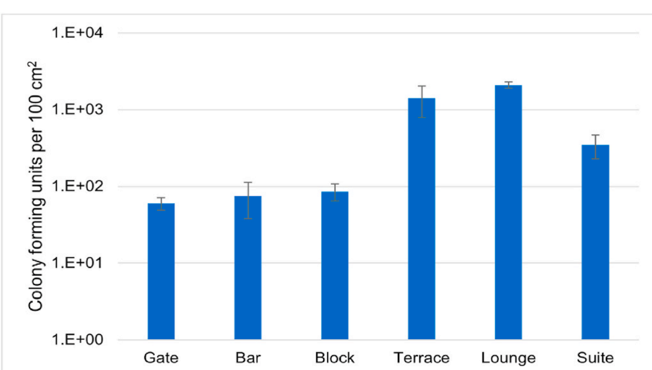

Fig. 15. Mean bacterial colony forming unit counts for different arena areas; standard error for all sample types is shown (gate $n = 6$; block $n = 12$; terrace $n = 4$; lounge $n = 10$; suite $n = 19$).

A significant difference in CO_2 concentrations between rows closer to the stage and rows higher up was also noted in proscenium stage-type theatres with seating divided into three tiers (usually stalls, lower circle and upper circle). Those seated higher up in the venue, such as those in the Circle and Balcony seats in the Lyceum Theatre (Fig. 3), and The Grange Opera (Fig. 6) auditoria were exposed to higher CO_2 concentrations. The concentrations between lower and higher tier rows varied by up to 57% in The Grange and 34% in Lyceum which can also be related to the types of ventilation systems in those auditoria.

The CO_2 data from the Piccadilly Theatre (Fig. 5) event suggests that the Stalls (bottom) and Grand Circle (top) tiers of the auditorium had lower CO_2 concentrations than the Royal Circle (middle) tier. This could be due to the poor mixing of air in the Royal Circle, but such a statement cannot be made with certainty as researchers present on-site observed that this was the busiest auditorium area.

In Leeds Playhouse (Fig. 4), a variation of CO_2 was also observed between rows, but only events with occupancy up to 24% capacity were monitored. ACC Main auditorium (Fig. 8a) and O2 Arena (Fig. 7) events had low occupancy as well. Hence, conclusions on how well mixed the space, in low occupancy events, is cannot be made unless the exact seating and spectator numbers in each area are known.

Many of the auditoria used ventilation systems which supplied air at the bottom of the auditoria and extracted it at the top (Grange, O2, ACC) and so, by their design, CO_2 concentrations and any virus-laden aerosols will be at greater levels with increasing vertical height. Due to this, it is important to ensure good mixing of air at upper seating levels. Occupancy information provided certainty in making conclusions about the mixing of air in highly occupied events and allowed events when such conclusions could not be made with certainty to be identified.

The results (Fig. 9) show that the theatre auditoria were generally well-ventilated in terms of CO_2 concentrations, relative to the occupancy levels and should be considered low-risk environments for occupants with respect to the long-range transmission of airborne disease [38–41]. Whilst mean CO_2 concentrations were generally low throughout the

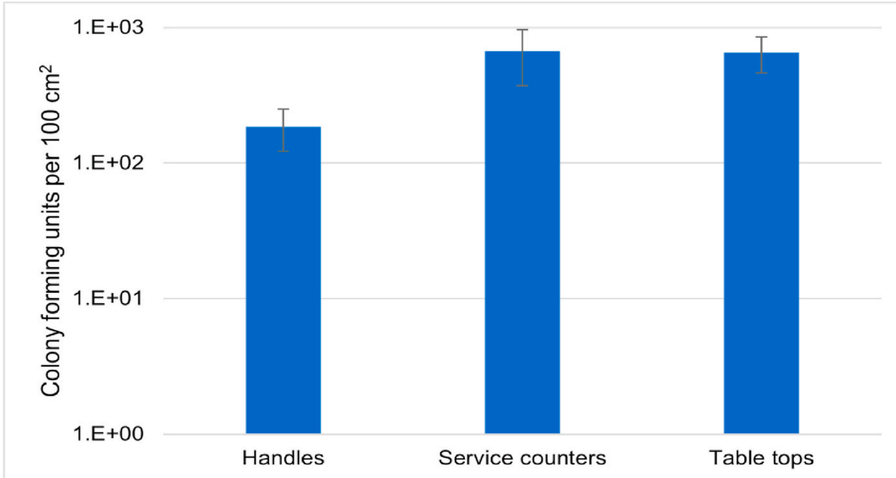

Fig. 16. Mean bacterial colony-forming unit counts for different surface types; standard error for all sample types is shown (handles $n = 9$; service counters $n = 12$; table tops $n = 26$).

seven venues (Fig. 9a), with the majority of spaces being classed as Band A or B, in the maximum CO_2 classification (Fig. 9b) 24% of spaces were class E. The maximum CO_2 for each auditorium was corespondent to the event of maximum occupancy. Showing that ventilation in some spaces should be improved druing high occupancy.

The same observation about occupancy effects on ventilation can be made from occupancy and CO_2 analysis. In the Lyceum (Fig. 10), Grange (Fig. 11) and Crucible (Fig. 12) there is a rise in maximum CO_2 values with increasing occupancy, indicating that ventilation systems are not demand-driven.

Volume per person and CO_2 analysis (Fig. 13) also showed that ventilation can be improved for high occupancies, especially in the Crucible. There is a trend between decreasing volume of air per occupant and increasing average CO_2 levels. Capturing more high occupancy events in the auditoria would likely make this trend more prominent. Due to a large space volume relative to occupancy levels, there was a negligible spatial variation in CO_2 concentration observed in the ACC main auditorium and the O2 Arena. This could be attributed to the ventilation system providing better mixing of air in the space or, as previously stated, the events being run at a significantly reduced capacity. A large vertical height within a venue, corresponding to a large total volume and therefore a larger volume per person, is found to reduce occupant risk of exposure to higher CO_2 concentrations indicative of exhaled breath.

From high-resolution CO_2 data, occupancy analysis and ventilation system effectiveness evaluation, general recommendations were made (Section 4.4) as well as recommendations to venue managers and event operators.

4.2. Microbiological sampling in the O2 arena

No standards or guidance specify normal or target bacterial counts for surfaces and air in public spaces. Such standards do exist for healthcare and pharmaceutical production premises. Acceptable bacterial numbers on surfaces in low-to medium-risk healthcare areas are in the 5–10 CFU per cm^2 [42,43] and similar levels are also given for pharmaceutical production [17]. The highest value for any surface sampled at the arena was 30 CFU/cm^2, with the means for any particular area ranging from 0.6 to 2.16 CFU/cm^2. The CFU numbers obtained from our analysis do not indicate that surface contamination by bacterial organisms would pose a health risk. However, the organisms isolated were not identified so we cannot say anything about the presence of any specific microbial pathogens.

SARS-CoV-2 was detected on 8.5% of all surfaces sampled. While the copy numbers detected were extremely low and very unlikely to cause a risk of transmission, the fact that SARS-CoV-2 RNA was detected at the venue indicates that individuals shedding the virus were present at the event. The O2 Arena was opened especially for this event after many months of lockdown and all staff and spectators were required to perform a lateral flow test with a negative result before entering the arena. The presence of SARS-CoV-2 RNA indicates that there were likely some false-negative tests or incorrect reporting. Seating blocks that were better ventilated than lounges, terraces, and suites had lower bacterial counts than the latter stated places.

As for surfaces, guidance and standards for acceptable levels of bacterial counts in the air in public spaces are lacking. The guidance states that bacterial colony counts (CFUs) per m^3 of air in an operating theatre should be < 180 [16] and a similar standard exists for packing areas in pharmaceutical production premises (<200 CFU/m^3 [17]). Guidelines for the air quality of office space produced by the Ministry of the Environment in Singapore state that bacterial counts should not exceed 500 CFU/m^3 [18].

A limitation of the work presented is the size of the microbiological dataset, which is too small to accurately estimate if there is a strong correlation with CO_2 data in the O2 Arena. However, it provides valuable information on the presence of bacteria in air samples and the SARS-CoV-2 virus.

The CFU per m^3 numbers from samples collected during the event held in the arena were an order of magnitude higher than those quoted in the above guidance, which is understandable in a heavily occupied event venue but indicates that when transmissible diseases are present in the audience then there may be transmitted in such settings and this requires further investigation.

4.2.1. Limitations and further work

The analysis in this paper did not include a relative exposure index model, such as those presented by Ref. [14]. Future work could conduct a risk assessment using such models.

It was assumed that any increase in CO_2 concentration above expected ambient levels (400–450 ppm) was attributed to human exhalation. However, on one occasion it is believed that an addition source of CO_2 was present at the end of the event in the Crucible auditorium (Fig. 2). A “ticker tape” cannon was used, and this uses CO_2 as a propellant, and this caused a temporary increase in the CO_2 concentration. Furthermore, theatrical smoke may have been used during some events, but there is no direct record of this. Many of the events were attended by the research team and good communication with event managers ensured that this uncertainty only applies to a small number of events in select venues, but it is recommended that caution needs to be exercised when monitoring CO_2 at live events.

Occupancy as a percentage of total capacity was in some cases very high (e.g., the Crucible, the Grange, and the Lyceum all had events >88%). However, at some events, the venues were under-occupied compared to how they would usually be operated, and extrapolation of results in not appropriate.

Ventilation was estimated (Table 4) for all seven auditoria assuming well mixed, homogeneous CO_2 concentration. The high-resolution CO_2 data presented in this paper suggests that a well-mixed assumption does not apply to many theatre auditoria, and hence the ventilation calculations could be unrealistic. The methodology used to estimate the ventilation rates also assumes that the auditoria were empty when the CO_2 decay occurs, which cannot be confirmed with absolute certainty.

Thermal comfort was beyond the scope of this paper; however, it could be a legitimate concern if the auditoria were overventilated leading to airspeeds higher than would be considered comfortable.

Finally, this paper has only reported the carbon dioxide concentrations and microbiological sampling in the main auditoria, however, there are other spaces which people occupy during events such as bars, ticketing areas, and toilets where they will also be exposed to exhaled breath and, potentially, airborne viruses. Although these types of ancillary spaces might only be occupied briefly by individuals (e.g. toilets), ventilation may be limited, room volumes small, and if there is a high turnover of people entering and exiting, they may be almost permanently occupied by at least one person. Attention should be paid to these areas in future work, although a small selection of results from these types of spaces was presented in Malki-Epshtein et al. [13].

4.3. Recommendations

Intervals, i.e., short breaks in between parts of the performance, are effective ways to reduce indoor CO_2 concentration. In the Lyceum Theatre (Fig. 3), Grange Opera (Fig. 6), and Crucible Theatre (Fig. 2) events, the timing of the interval and subsequent reduction in CO_2 concentration is evident. In poorly ventilated or highly occupied venues, more frequent intervals might be a useful option to reduce indoor CO_2 concentration. Reduced CO_2 concentration indicates a greater provision of fresh air per occupant and a reduction in long-range transmission of potentially virus-laden aerosols. In the case of Grange Opera, which had a very long interval period (100 min) during which the audience left the auditorium, the average CO_2 for the event is non-dependent on the increasing occupancy (Fig. 11). The levels reduce to match outdoor levels during the interval and this results in shortened exposure time to exhaled breath. However, the crowding that may occur as people leave and return to the auditorium during the interval may increase close contact between attendees (especially if they occupy densely occupied areas such as toilets and bars) and so enabling short-range droplet transmission [8].

Besides regular intervals, there are other recommended strategies that venue operators can use to reduce occupant exposure to exhaled breath (as a proxy for the long-range transmission of infected aerosols) such as ensuring that ventilation rates in venues are high, the indoor air is well-mixed and well distributed, and that the space volumes are large relative to the number of occupants. However, venue operators are also concerned about operating costs and thus the energy required to provide heating and cooling of the incoming air.

Many venue operators commented that the ventilation systems were providing full outdoor air, i.e. not tempering the incoming outdoor air by mixing with indoor air and that they had overridden building management systems so that ventilation rates were at their maximum. This was often done by setting very low CO_2 concentration thresholds. Whilst unusually high ventilation rates might be a good strategy to reduce long-range transmission of airborne disease (which was the ultimate aim of the Events Research Programme) and to allow for the reopening of mass-gathering events in England, long-term plans for operating these types of venues must be mindful of the increased energy consumption associated with higher ventilation rates in mechanically ventilated buildings.

The findings apply to other buildings of similar size, with similar space volume to occupancy ratios, and with similar ventilation strategies and ventilation rates, besides the ones monitored, and should give venue operators the confidence to operate, and audiences the confidence to attend, mass-gathering events in these types of spaces, assuming other transmission routes are accounted for.

Ventilation is a non-pharmaceutical intervention which can prevent the spread of airborne disease amongst a population by diluting the concentration of virus-laden aerosols in the air of a space [9]. Ventilation should be used in conjunction with other pharmaceutical and non-pharmaceutical interventions to prevent the spread of airborne diseases, such as vaccination, physical distancing [41], isolation of infected individuals, hand-washing, and mask-wearing [44].

5. Conclusions

To assess the risk of reopening mass-gathering events in theatres after the COVID-19 pandemic, a measurement campaign of high-resolution indoor CO_2 concentrations was carried out in seven theatres in England, during 2021. Monitoring multiple theatres which had different operators, and capacities and were built in different decades resulted in conclusions and recommendations generally applicable to the majority of theatre auditoria in England.

Effective ventilation does not only depend on ventilation rates but also on the appropriate distribution of outdoor air to all areas. Hence, deploying a high-resolution CO_2 monitoring methodology in large spaces, such as theatre auditoria, is crucial.

Although most of the theatre auditoria monitored had air quality classed as excellent or very good, which indicated that ventilation rates were sufficient relative to occupancy levels, some seating areas were exposed to poor mixing of air and much higher CO_2 levels.

Occupancy and CO_2 analysis showed that demand-driven ventilation systems do not always work as intended. Moreover, it highlighted that introducing longer intervals can lead to a significant reduction of average CO_2 in space over the duration of an event. Observations of how occupancy and volume of air per person affect the air quality (with CO_2 as a proxy) indicate that ventilation could be improved for highly occupied events.

Microbiological sampling of surfaces and air in the O2 arena showed bacterial numbers in line with what would be expected at such an event. The detection of SARS-CoV-2 RNA at low concentrations in a minority of samples suggests that individuals shedding the virus were present at the event, however, the copy numbers detected would not present a transmission risk.

The work has demonstrated that suitable ventilation strategies are in place to enable the operation of public events in theatres with a low risk of long-range transmission of COVID-19 or other airborne diseases, for relative occupancies.

Ventilation should be used in conjunction with other interventions to prevent the spread of airborne diseases, such as vaccination, physical distancing, isolation of infected individuals, good hygiene practices and mask-wearing.

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CRediT authorship contribution statement

Filipa Adzic: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ben M. Roberts:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Elizabeth Abigail Hathway:** Writing – review & editing, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Rupy Kaur Matharu:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lena Ciric:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Data curation. **Oliver Wild:** Writing – review & editing, Software, Investigation, Data curation, Conceptualization. **Malcolm Cook:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation. **Liora Malki-Epshtein:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

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.

Data availability

Data will be made available on request.

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Appendix A

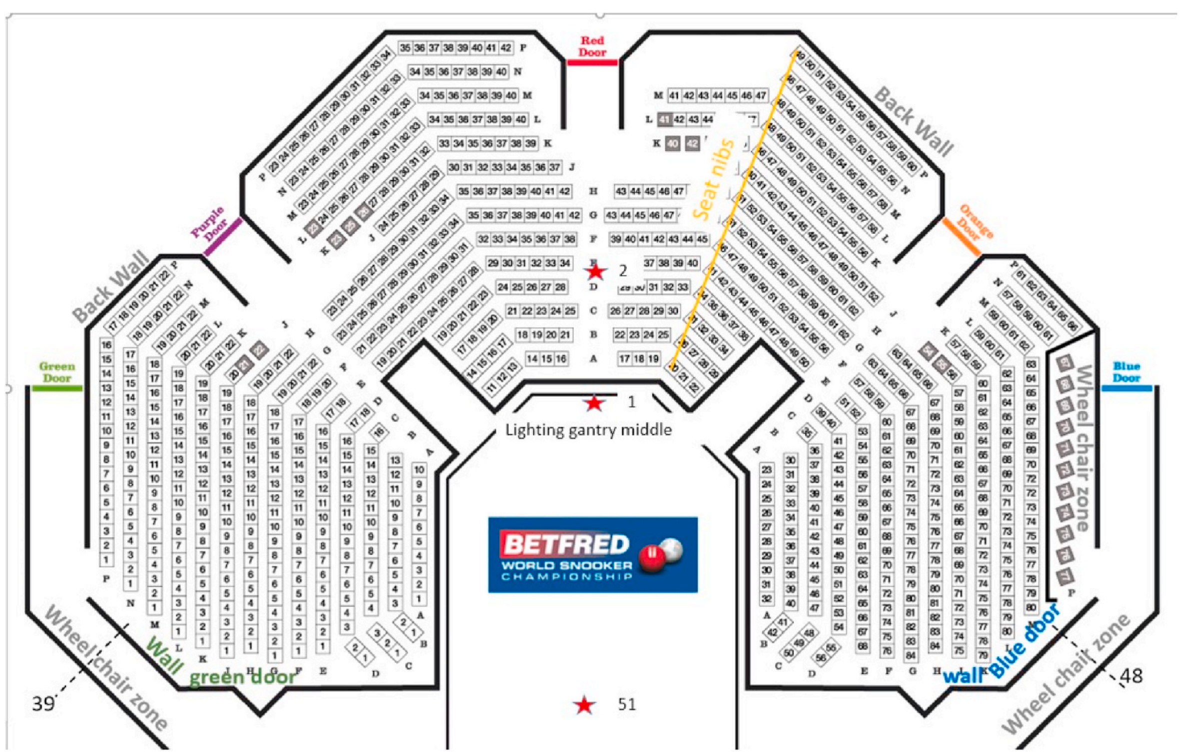


Fig. A.1. Crucible auditorium seating plan [45]

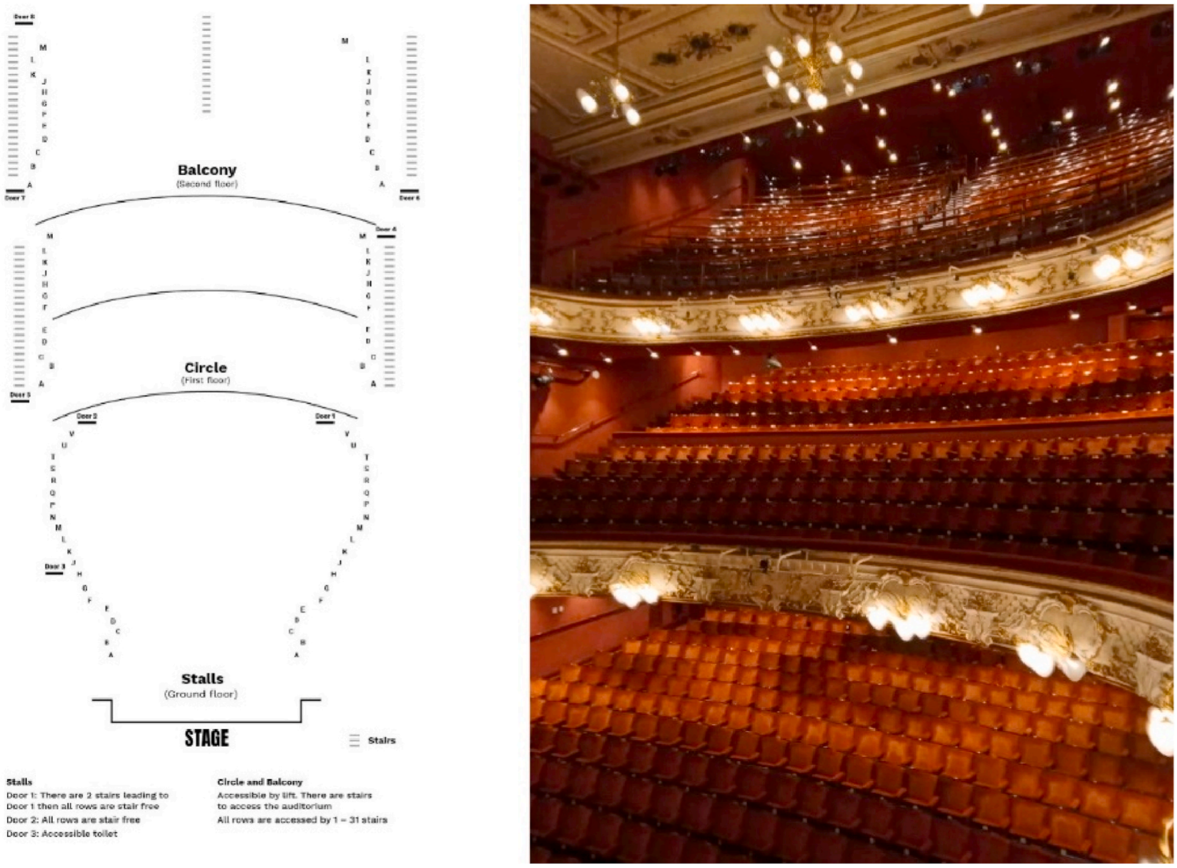


Fig. A.2. Lyceum theatre seating plan and auditorium [46].

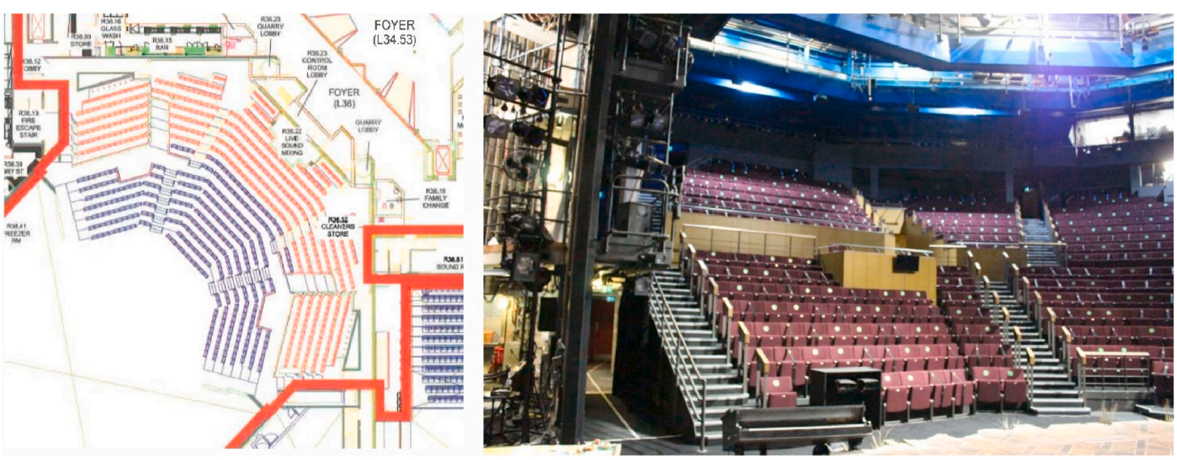


Fig. A.3. Leeds Playhouse (Quarry theatre) seating plan and auditorium [47].

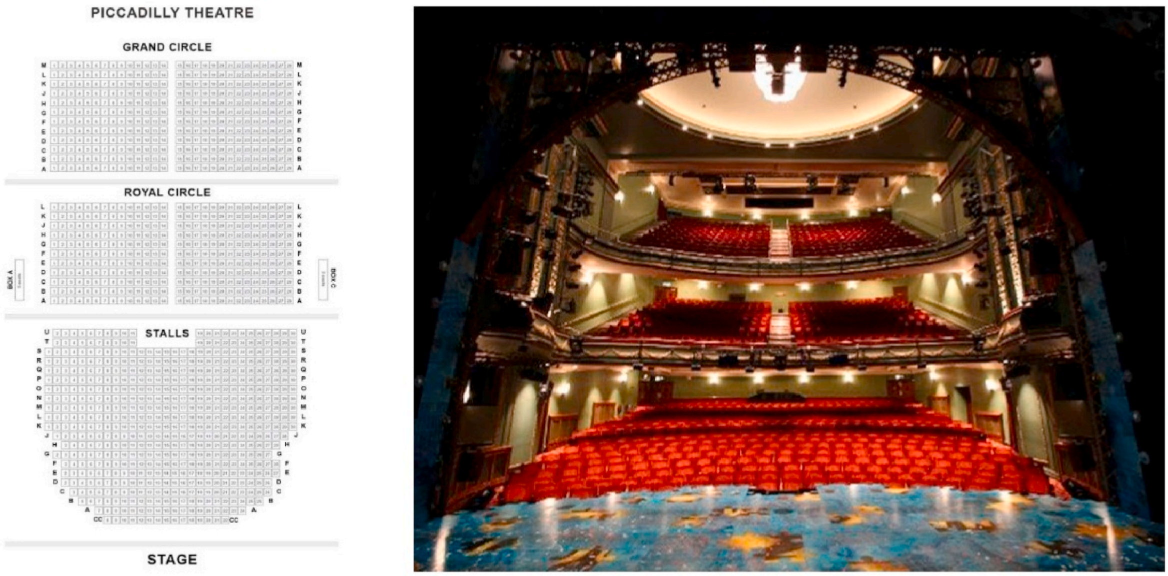


Fig. A.4. Piccadilly Theatre seating plan and auditorium [48].

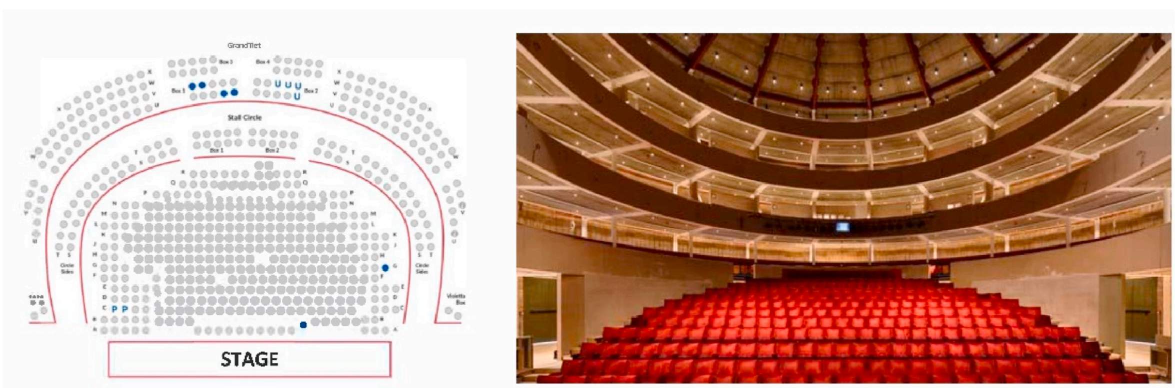


Fig. A.5. Grange Opera House seating plan and auditorium [49]

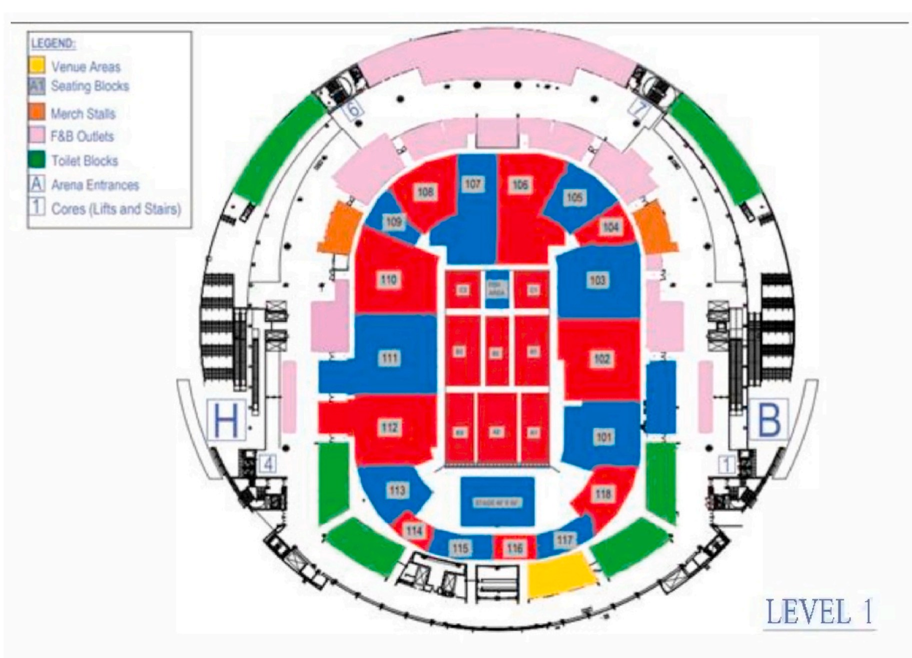
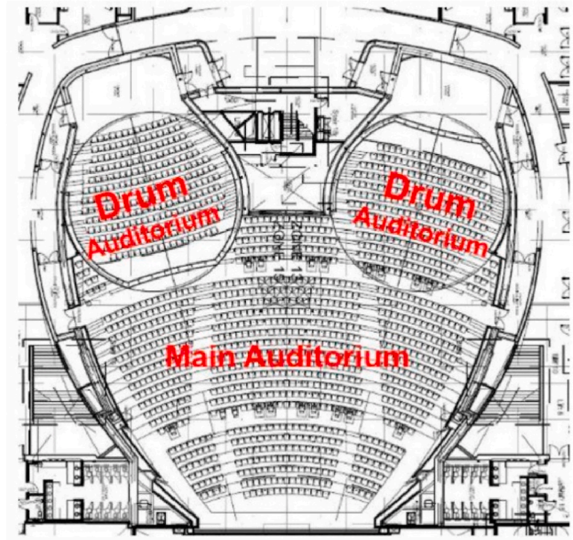
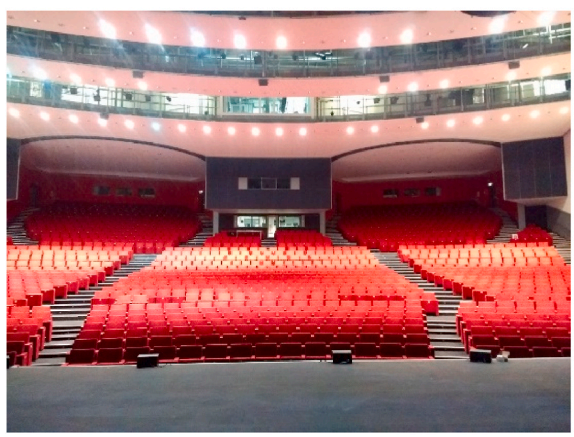


Fig. A.6. O2 Arena seating blocks level 1 (O2, 2022)



(a)



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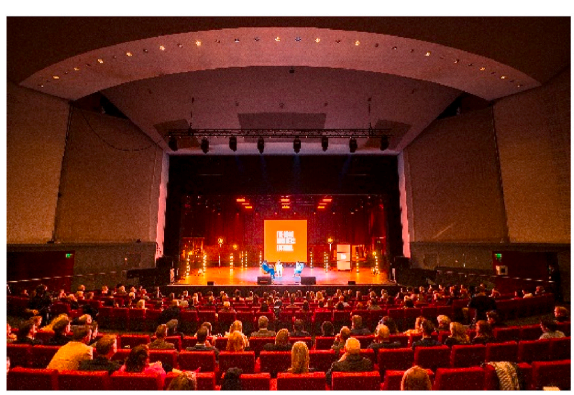

(c)

Fig. A.7. (a) ACC Main auditorium and "drum" auditoria schmatics [50] (b) ACC Main auditorium and drums (both in use) [50] (c) Event photos by Ant Clausen.

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