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Improving hospitality venue ventilation via behavioural change as a response to the COVID-19 pandemic

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ABSTRACT

The COVID-19 pandemic highlighted the importance of good ventilation in hospitality venues, given its role in reducing virus transmission. Small-scale hospitality venues (<50 employees) employ 98 % of staff in the UK hospitality sector. However, little is known about the current state of ventilation in these venues, the barriers to more effective ventilation, and whether behaviour change strategies can improve ventilation performance. This formed the aims of the current research. This work was divided into three phases: Phase 1 explored the current performance of ventilation in hospitality venues and the barriers to more effective ventilation; Phase 2 led to the co-creation of a behaviour change intervention consisting of guidance material and provision of a CO_2 monitor; and Phase 3 piloted the intervention, evaluating changes in behaviour and ventilation performance, in addition to assessing user acceptability of the intervention. Ventilation performance was identified to be below recommended standards in most participating venues. Business owners stated they were not able to improve ventilation due to a lack of clear guidance, lack of funds to upgrade systems, limited authority over building infrastructure, and competing priorities. In these businesses, customer comfort, atmosphere, noise control, and security were given greater importance than improving ventilation. The introduction of a guidance document and CO_2 sensors to monitor ventilation performance saw 3 of 6 venues increase ventilation actions such as window/door opening and/or the switching on of wall mounted fans. Following the intervention, business owners expressed an increased likelihood of purchasing air cleaners, or mechanical ventilation systems. However, their likelihood of purchasing CO_2 monitors decreased. The guidance is advised to be used alongside spot check CO_2 monitoring during periods of high occupancy.

1. Introduction

1.1. Background

The COVID-19 pandemic and the associated government-mandated lockdowns significantly impacted various sectors of the UK economy, with consumer spending on hospitality reducing to less than 70 % of pre-pandemic levels [1]. An early rapid review of studies exploring COVID-19 transmission within hospitality venues identified that closing indoor venues was the most effective measure for reducing incidence or mortality [2]. However, the impact of such closures on the hospitality sector, combined with the ongoing cost-of-living crisis, has been substantial - there has been a 30.6 % contraction in the UK nightclub sector since March 2020 and a 5.9 % drop in independently owned hospitality businesses in the year to May 2023 [3].

Several practical methods were employed across the hospitality sector to help reduce the transmission of COVID-19, without closure of businesses. These included: reduced venue occupancy, increased cleaning frequency, provision of hand-sanitiser, etc. However, several case studies have highlighted the importance of airflow and ventilation for reducing the transmission of COVID-19 within venues [2]. The UK's Events Research Programme (ERP) utilised high-resolution Carbon Dioxide (CO_2) monitoring to investigate ventilation performance at large-scale events in theatres, sports stadia, and temporary events spaces

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(music festival tents) demonstrating a range of environmental conditions depending on venue type. The ERP found that public and business understanding of ventilation as a means to reduce COVID-19 transmission was lower than measures such as cleaning and hand hygiene [4].

A key limitation of the ERP was the restriction to large-scale events held at some of the UK's largest venues. Small and micro-scale hospitality venues (with fewer than 50 employees) comprise 98.4 % of the UK's hospitality sector [5], and as such, are a critical subsample to research. This is particularly the case given that building construction, available technology, and employees' knowledge and motivations are likely to be substantially different in smaller businesses. For instance, they are much less likely to have dedicated building specialists on site. Other than surveys of restaurant owners in Kuala Lumpar [6] there has been no research to identify what technical and behavioural solutions would be suitable for small-scale venues. Hence, there is an acute need to understand the ventilation performance and behaviour of these hospitality venues to protect both employees and the public from the airborne transmission of pathogens and other pollutants, and support future pandemic preparedness.

1.2. CO_2 monitoring as an indicator of ventilation performance

The monitoring of CO_2 concentrations provides an effective proxy for occupancy and/or ventilation performance in buildings [7]. CO_2 is present in the exhaled breath of venue occupants; it therefore represents the fraction of air that has been exhaled by individuals in the space. As a result, the use of CO_2 monitors can be a cost-effective method for identifying spaces with poor ventilation (i.e., those where CO_2 is not effectively removed and diluted by outside air) and actively managing ventilation, though it is important to note that CO_2 is not a direct proxy for infection risk from airborne pathogens.

Guidance prepared by the Environmental Modelling Group (EMG) and Scientific Pandemic Insights Group on Behaviours (SPI-B) in 2021 identified two generic CO_2 concentration thresholds to indicate if a venue was well- or poorly-ventilated [7]. CO_2 concentrations consistently below 800 ppm are likely to indicate that a venue is well ventilated, whilst sustained values above 1500 ppm are likely to indicate poor ventilation and a need for mitigation. This provides a good benchmark for assessing venue performance, although there are other methods of ranking indoor air quality (e.g. British Standards Institution [8]; Malki-Epshtein et al. [9]).

1.3. Behaviour of building occupants

Existing research in other sectors indicates that ventilation of indoor spaces is significantly influenced by occupant behaviour. Studies in office buildings have revealed distinct patterns, showing that windows are opened less frequently in winter compared to summer, and that these patterns change more frequently during the spring and autumn seasons [10,11]. This behaviour is believed to be driven by factors such as temperature control and a desire for fresh air [11,12]. Several studies have also evaluated whether the use of CO_2 monitors and provision of associated guidance, can alter behaviour to improve ventilation. In particular, the use of CO_2 monitors in schools has been trialled in several countries and shown to reduce CO_2 levels [13,14]. Thermal comfort has been highlighted as an issue for responding to audio warnings of poor ventilation in colder countries [15] with other studies offering guidance for purge ventilation during breaks to avoid discomfort [16]. Cold discomfort has been further highlighted as a primary barrier to opening windows in response to CO_2 monitor warnings in hospital settings [17].

Despite this insight, current understanding of occupant behaviour in relation to ventilation in hospitality venues, remains limited. The Capability Opportunity Motivation (COM-B)and the Behaviour Change Wheel approach in which it is situated [18,19] form a widely-used behavioural science framework that can be applied to better understand and increase ventilation behaviours in the hospitality sector. The Behaviour Change Wheel framework incorporates mechanisms implicated (and evidenced) in multiple theories of behaviour change, providing a highly comprehensive and flexible system for understanding and changing behaviour. Indeed, the COM-B model is included in the UK National Institute for Health and Care Excellence public health guidelines for behaviour change [20]. According to the COM-B model, for a behaviour to occur, an individual must possess the relevant physical or psychological skills (capability), have access to necessary physical or social resources (opportunity), and must perceive the need (reflective motivation) or feel inclined to engage in the behaviour (automatic motivation). The 'behavioural diagnosis' enabled by the COM-B can then be linked to appropriate behaviour change strategies via the Behaviour Change Wheel. For example, while motivational barriers may be addressed through persuasive strategies, gaps in knowledge or understanding are best addressed through education. Numerous studies have effectively applied the COM-B model to understand compliance with measures to reduce COVID-19 transmission. For example, Gibson Miller et al. [21] identified reflective motivation as a significant driver of hygienic practices; Armitage et al. [22] implicated automatic motivation and social opportunity in wearing of face masks, whilst Burton et al. [23] revealed that reflective motivation, psychological capability, and social opportunity played vital roles in compliance with social distancing guidelines. Similarly, behaviour change interventions have been effective in promoting behaviours central to the UK government's public health response to COVID-19, including wearing of face masks [24], vaccination uptake (see [25] for a systematic review) and physical distancing (see [26] for a systematic review). Understanding the factors underlying occupant ventilation behaviours is therefore critical to develop effective strategies to improve ventilation in hospitality venues, ultimately creating a safer environment for both customers and staff.

1.4. Aims & objectives

This programme of research aims to examine the current state of ventilation performance in small-scale hospitality venues, and barriers to more effective ventilation in these venues for the first time, to enable the novel development and testing of a behaviour change intervention to improve ventilation practices. This will be achieved via the following objectives:

i. Establish the existing ventilation performance of a range (type and size) of hospitality venues within Sheffield, UK.
ii. Understand hospitality business owners' capability, opportunity, and motivation to engage in ventilation practices.
iii. Develop clear guidance that can be applied in small-scale hospitality venues to improve ventilation performance, through co-design with beneficiaries and stakeholders.
iv. Pilot the acceptability and effectiveness of the developed guidance in fostering behavioural change and enhancing ventilation performance.

2. Methods

2.1. Design and setting

This work is divided into three distinct phases: Phase 1 established the current state of ventilation in hospitality venues and barriers to more effective ventilation practices; Phase 2 led to the co-creation of guidance material to help improve ventilation in hospitality venues; and Phase 3 piloted the intervention, evaluating changes in behaviour and ventilation performance, in addition to assessing user acceptability of the intervention.

Phases 1 and 3 were mixed-methods studies comprising venue observations, Carbon Dioxide (CO_2) concentration monitoring, participant interviews (Phase 1) and behavioural questionnaires (Phase 3). Each phase of the study was granted ethical approval from the Psychology Ethics Subcommittee at the University of Sheffield.

2.1.1. Phase 1: Establishing the current state of ventilation in hospitality venues

2.1.1.1. Participating hospitality venues. A set of 19, independently owned, hospitality venues (three cafés, seven restaurants, six bars, and three nightclubs) participated in Phase 1 during November 2021 to February 2022. Venues were recruited via door-to-door solicitation by researchers in Sheffield, UK. Some venues were approached and invited to join the study during an Environmental Health visit, these were followed up with phone calls and/or emails from researchers. Approximately 100 venues were asked to participate in the study. The venue types were chosen following discussion with local environmental and public health teams. These were independently run, small scale, hospitality venues with no in house engineering expertise. A range of venue types from cafés to nightclubs was considered to cover a range of occupancy densities. A single nightclub with in-house engineering expertise was included in the study due to their interest in the aims of the research. This provided a useful comparison for later analysis. Upon completion of Phase 1, each participant was provided with tailored feedback and advice on their current state of ventilation and methods for improvement alongside a £ 20 e-voucher incentive. Full informed consent was obtained from participants during the initial venue visit.

Venue size, existing ventilation practices and opportunities for improvement were determined during the initial site visit. Table 1 provides an overview of the main characteristics, further details are provided in the associated online data [27]. During the visit full measurements were taken from the public spaces (including opening areas for ventilation) and relevant technical details, where available, were taken from ventilation units. Venue owners provided information on the maximum capacity of the venue based on fire safety and licensing. Venues defined as having "natural ventilation" mean that there are openings the owners can use to provide outside air (e.g. windows, external doors). Centralised mechanical ventilation includes systems with a central air handling unit and air ducted to diffusers (where provided) throughout the space. Wall-mounted fans are where fans are provided in the wall of the venues as either supply or extract fans. Although all venues are defined as having a 'type' of ventilation this does not mean it was sized, or operating to provide adequate fresh air. The use of air purifiers/cleaners is noted in the table for completeness, although this will not affect the CO_2 readings. Ventilation practices were confirmed via visual observation, and business owners were relied upon to explain how ventilation systems were used, e.g. when and how frequently windows were opened. Not all venues were confident of their current ventilation practices and whether all systems were functioning as intended.

2.1.1.2. Carbon dioxide concentration monitoring. CO_2 monitoring was conducted to identify whether ventilation was adequate or poor in participating venues. Two types of CO_2 sensors were used in this study, both employing Non-dispersive Infrared (NDIR) technology (Table 2). A comparison of these two sensors is presented in Supplementary Material Section S1. CO_2 monitoring was conducted over a 2-week period, or in some cases, single events, depending on venue type. Participating venues were restricted from viewing live CO_2 data to prevent changes to ventilation practices prompted by awareness of CO_2 levels.

The CO_2 monitors were installed in the main public areas of each venue, where customers spend the most time (staff spaces, kitchens, and toilets were not monitored). Multiple CO_2 monitors were deployed in each venue to capture a reasonable picture of CO_2 distribution (Table 1). The number of sensors used varied depending on venue size and layout (an example layout is provided in Wood et al. [27]) Except for nightclubs, CO_2 monitors were mounted on the walls of the venue at a 2 m height from the floor. For nightclubs and bars with high ceilings, the CO_2 monitors were affixed to the rear of lighting or audio-visual systems to prevent tampering by venue patrons. These CO_2 monitors were typically mounted at heights between 2 and 3 m, with a few up to 3.6 m. All sensor heights are detailed in Wood et al. [27]. All CO_2 monitors were installed in slow-moving air areas away from draughts or ventilation jets. Each monitor was positioned at least 0.5 m away from people or openable windows/doors.

The following metrics were calculated based on the collected CO_2 concentration data to assess the ventilation performance of each venue:

i. Max CO_2: the maximum recorded CO_2 concentration from all sensors in a venue.
ii. Median CO_2: the median recorded CO_2 concentration from all sensors in a venue during opening hours.
iii. Percentage of opening hours $CO_2 > 800$ ppm: the total time that CO_2 concentrations exceed 800 ppm divided by the known

Table 1
Phase 1 venue characteristics.

Venue ID	Business Type	Venue Area (m^2)	Venue Average Ceiling Height (m)	Maximum Capacity (No. of People)	Maximum Occupancy‡ (No. of People)	Opening Hours (hours/day)	Ventilation Type*	No. of CO_2 Monitors
1 R	Restaurant	229.5	2.4	100	18	9–10	MV	4
8 R	Restaurant	44.1	3.0	25	10	9–14	NV	3
9 R	Restaurant	68.5	2.5	40	20	6–9	NV, WM, F, AP	4
11 R	Restaurant	87.5	2.5	47	15	12–14	NV	3
12 R	Restaurant	87.3	2.8	25	25	12–13.5	MV, NV	3
13 R	Restaurant	83.9	2.5	36	15	11	NV	3
19 R	Restaurant	175.5	3.3	100	80	7–9	NV	4
2 C	Café	101.1	3.5	50	17	9	MV	4
3 C	Café	195.8	2.9	90	70	10	WM, F	4
14 C	Café	206.7	2.9	100	100	8–12	MV	4
4B	Bar	178.6	2.8	100	80	7–8	NV	6
10B	Bar	186.3	3.0	120	120	5–11	NV, WM, F	6
15B	Bar	488.3†	2.7	300		13	MV	7
17B	Bar	240.5	4.9	100		2–3.25	MV	4
20B	Bar	91.1	2.8	50		7	NV	4
21B	Bar	297.5†	2.8–3.4	280	120	13	NV	13
5 N	Nightclub	162.2	5.3	1500	130	13	MV	9
6 N	Nightclub	1026†	5.7	1300		10	MV	11
16 N	Nightclub	887†	3.2	1800	1800	6	MV	7

*NV: Natural ventilation. MV: Centralised Mechanical ventilation. WMF: Wall mounted fans. AP: Air purifier.
†Venues are spread across three rooms. ‡ Maximum occupancy during study estimated by venue owners.

Table 2
Carbon dioxide monitor specifications.

Sensor	Accuracy	Resolution	Range	Sampling Period	Data Visualisation	Other Data Collected
SenseAir	±30ppm, ± 3 % of reading	1 ppm	400 – 10,000 ppm	5 min*	Web UI, Data download	Temperature, Humidity
Arnoux CA1510	±50ppm, ± 3 % of reading	1 ppm	400 – 5000 ppm	2 min	LCD Display, Data download	Temperature, Humidity

* Three venues were recorded at 20-min intervals: 1 R, 2 C and 3 C.

opening hours. Time starts when any sensor in a venue exceeds 800 ppm and stops when all sensors within a venue are at or below 800 ppm. Opening hours were provided by venue owners.

iv. Percentage of opening hours $CO_2 > 1500$ ppm: the total time that CO_2 concentrations exceed 1500 ppm divided by known opening hours. Time starts when any sensor in a venue exceeds 1500 ppm and stops when all sensors within a venue are at or below 1500 ppm. Opening hours were provided by venue owners.

The collected CO_2 data was also used to determine the probability of exceedance for CO_2 during venue opening hours. The probability of exceedance was calculated for each recorded CO_2 level by dividing the number of readings greater than the recorded CO_2 value by the total number of readings. Whereby, a CO_2 reading of 400 ppm has a probability of exceedance of approximately 1.0 as this is within the 400–420 ppm typical range of atmospheric CO_2 concentration. When the probability of exceedance reduces to 0.0, this indicates that no CO_2 concentrations were recorded above the corresponding CO_2 concentration during the venue's opening hours.

2.1.1.3. Occupancy monitoring. Estimates of occupancy were reported by the business owners for most venues (Table 1), including indications of their busiest day/days during the trial. In most cases, occupancy was below the maximum venue capacity as the venues were deliberately operating at lower capacity (particularly the restaurants and night clubs) in response to COVID-19 controls.

2.1.1.4. Interviews. Semi-structured interviews (20–65 minutes in duration) were conducted by 1–2 interviewers with 20 people from participating venues (8 venue owners and 12 venue managers). One participant owned one venue (1 R) and managed another (2 C) and took part in a separate interview for each venue. Two venues (19 R and 20B) were run by the same managers who took part in one interview about both venues. One venue owner required a language translator (13 R), therefore any quotes from this interview are in third person. All interviews were audio-recorded and transcribed verbatim. Due to a fault with the recording equipment, data from one interview (17B) were lost and have not been included in interview analyses.

The interview schedule was based on the COM-B model (e.g., Michie et al. [19]), and was designed to explore participants' capability, opportunity, and motivation to engage in ventilation practices related to reducing COVID-19 transmission (Supplementary Material S2). Specifically, interview questions were designed to tap into people's capability (e.g., knowledge that ventilation reduces COVID-19 transmission), opportunity (e.g., whether the physical characteristics of their venue allow for effective ventilation), and motivation (e.g., whether they felt responsible for doing what they could to reduce COVID-19 transmission). Interviewers prompted and explored issues in more depth where appropriate, encouraging participants to recall any explicit instances to elaborate on the topics under discussion. This method allowed unprompted and unanticipated information to emerge.

Anonymised interview transcripts were coded with the aid of NVivo qualitative data analysis software and analysed according to the six phases of reflexive thematic analysis [28] which included: (1) Familiarisation with the data; (2) Initial coding, iteratively developing frameworks via inductive (identifying key phrases related to ventilation barriers and enablers) and deductive (mapping codes to COM-B categories) methods; (3) Searching for candidate themes from organised codes; (4) Reviewing and comparing themes to identify similarities and differences, organised within COM-B domains; (5) Refining and naming themes and sub-themes; (6) Assimilating analytic narratives and data extracts into coherent theme-based stories.

Thematic analysis phases 1–2 were conducted independently by researchers SP, AS and PB and agreements were reached by discussion. Phases 3–4 were conducted independently by researchers SP and PB and consensus was reached by discussion. Phases 5–6 were conducted independently by SP and feedback was provided by PB, CW and AH, according to which appropriate revisions were made.

2.1.2. Phase 2: Co-creation of guidance material to improve ventilation in hospitality venues

Phase 2 involved the co-design of a behaviour change intervention for evaluation in Phase 3. The co-design process was informed by the double diamond model [29] and included a combination of workshops and online surveys with environmental health officers (n = 100) and owners and managers of hospitality venues (n = 63) to develop and refine the intervention. The aim of this approach was to ensure the intervention was accessible to business owners, and not to define the technical requirements for improving airflow which was provided by the engineering research team (AH and EM). The technical aspects of the guidance were developed based on walkaround surveys in phase 1 and aligned with current guidance from SAGE EMG and CIBSE [30–32].

Environmental health officers were recruited through city contacts and did not receive any monetary incentive for participation. Hospitality venue owners/managers who engaged in face-to-face workshops were recruited through e-mail and door-to-door solicitation, receiving £ 80 in vouchers as remuneration. Those participating in online surveys were recruited via the Prolific research participation platform and received £ 3.20 for taking part. Workshop participants provided verbal informed consent; online survey participants indicated their consent to participate online.

Environmental health officers' expertise is based on their knowledge of environmental health regulations and working with businesses in the community. For owners and managers of hospitality venues, their lived experience of the impact and challenges related to ventilating their venues on a day-to-day basis was critical. Both groups of participants were likely to yield valuable insights into overcoming the barriers to ventilation in business venues. Co-production principles informing the workshops and online surveys included: (1) encouraging participants to contribute to the development of the intervention using a structured, participatory approach; and (2) ensuring participant voices were heard and ideas evaluated and acted upon.

Five separate co-design workshops took place sequentially with hospitality venue owners, managers and employees (Workshop 1, n = 3) and environmental health officers (Workshop 2, Workshop 3, n = 4; Workshop 4, n = 3; Workshop 5, n = 197[2]), facilitated by SP and ZM. Workshops focused on appraising evidence from the interviews in Phase 1, prioritising barriers to address within the key COM-B domains [19], and generating and evaluating possible solutions to be incorporated into

[2] Workshop 5 was conducted as part of a larger event.

the intervention, drawing on the intervention strategies and functions specified in the Behaviour Change Wheel [18,19]). For example, this included consideration of type, and depth of technical information, the barriers that needed to be overcome and what would motivate change. An initial intervention prototype was then developed and further refined based on online survey feedback obtained from owners and managers of hospitality venues (n = 63).

2.1.3. Phase 3: Observations of behaviour and ventilation practice pre- and post-guidance intervention

2.1.3.1. Participating hospitality venues. Nine hospitality venues (two cafés, two restaurants, four bars, and one community space) participated in Phase 3. Venues were recruited via door-to-door solicitation and targeted communication via telephone and/or email. Upon completion of Phase 3, each participant received a £ 100 e-voucher incentive. Full informed consent was obtained from participants during the initial venue visit. Venues were characterised using the same methods as Phase 1 (Section 2.1.1 Table 3).

2.1.3.2. Study timeline. The Phase 3 study ran across a two-week period in February and March 2023. At the initial venue visit (Time 1), the business owner/manager was asked to provide demographic and venue information and answered a questionnaire about their current practices and views on ventilation in the venue. During this visit, multiple CO_2 monitors were installed in the venue using identical methods to Phase 1 (Section 2.1.1). The first week of CO_2 monitoring in Phase 3 was designed to collect baseline venue data prior to the provision of the new guidance material (i.e. the behaviour change intervention). As such, the participating venues were restricted from viewing live CO_2 data to prevent changes to ventilation practices based on CO_2 readings.

At the end of week 1 (Time 2), the business owner/manager was provided with the new guidance material and asked to complete a second questionnaire assessing the prospective acceptability of the guidance. Live CO_2 monitoring data was then made available to the venue owner/manager either via the web portal (AirSense) or built-in LCD display (CA1510). CO_2 monitoring data was collected throughout week 2 to identify any systematic changes in ventilation levels.

At the end of week 2 (Time 3) the business owner/manager completed a third questionnaire assessing the retrospective acceptability of the guidance and answered questions about their ventilation practices and views on ventilating the venue.

Throughout the 2-week period, participants completed a daily behaviour diary (Supplementary Material S3) detailing the days and times the venue was occupied, which ventilation strategies were used and for how long each strategy was used before, during and after venue opening hours.

2.1.3.3. Acceptability questionnaire design. Acceptability questions assessed participants' views on different components of the ventilation guidance at Time 2 and Time 3 (Supplementary Material S4). Questions were based on Sekhon et al. [33] Theoretical Framework of Acceptability and adapted from Brook et al. [34] to measure acceptability of the overall infographic and the short-, medium-, and long-term actions suggested in the guidance across seven key domains: (1) affective attitude (e.g. how participants would feel/felt about using the guidance); (2) burden (e.g. how much effort it would take/took to use the guidance); (3) perceived effectiveness (e.g. how effective they perceived the guidance to be/was); (4) ethicality (e.g. whether they believed it was fair to have to use the guidance); (5) intervention coherence (e.g. whether the guidance made sense); (6) opportunity costs (e.g. whether using the guidance interfered with their other priorities); and, (7) self-efficacy (e.g. how confident they felt that they would be/were able to use the guidance effectively). Scores were aggregated to provide an overall mean acceptability score for each component of the intervention, with higher scores indicating greater acceptability.

2.1.3.4. Self-reported behaviour change. At Time 2 and Time 3, participants answered questions about how likely they would be to implement short-, medium-, and long-term actions from the guidance. At Time 3, participants reported whether they had implemented the short-term actions or used CO_2 monitors during the study period.

The raw data collected (including CO_2 readings, interview transcripts and questionnaire responses) is available online [27].

3. Results

3.1. Phase 1: Establishing the current state of ventilation in hospitality venues

3.1.1. Existing ventilation practices

Ventilation type and provision varied across venues (Table 1). All nightclub ventilation consisted of large centralised ducted supply systems that were sized for 5–6 air changes per hour. However, in most of these venues the equipment was old, mostly functional but lacking proper balancing and with poor quality louvres which may not promote adequate air mixing. Ventilation practices in bars, restaurants, and cafés were more varied, comprising centralised mechanical ventilation, wall-mounted fans, and natural ventilation. The condition of ventilation equipment varied between venues, and public nuisance laws in relation to late night noise [35] had negative implications for the use of natural ventilation practices. Smaller, low occupancy, venues with openable windows, or doors at both sides of a small seating area seemed able to manage the ventilation in their space well during the study period.

3.1.2. Carbon dioxide concentration monitoring

Fig. 1 presents some example CO_2 monitoring data from Venue 5 N on New Year's Eve 2021, where the four CO_2 metrics are clearly

Table 3
Phase 3 venue characteristics.

Venue ID	Business Type	Venue Area (m^2)	Venue Average Ceiling Height (m)	Maximum Capacity (No. of People)	Opening Hours (hours/day)	Ventilation Type*	No. of CO_2 Monitors
22 R	Restaurant	86.4	2.4	-	12 – 13	NV, WMF	2
23 R	Restaurant	163.7	3.4	80	4 – 7	NV, WMF	2
24 C	Café	33.3	3	37	7.5	NV, WMF	2
25 C	Café	54.8	2.4	30	6.5	NV	2
26B	Bar	197.2	2.9	100	11	NV, WMF	1
27B	Bar	168	2.7	170	7 – 11	NV, WMF	4
28B	Bar	94.1	3.3	100	8 – 12	NV, WMF	3
29B	Bar	153.0	3.2	87	10 – 11	NV, WMF	2
30 L	Community Space	199.2	4.5	160	3 – 4.5	NV	4

* NV: Natural ventilation. MV: Centralised Mechanical ventilation. WMF: Wall mounted fans. AP: Air purifier.

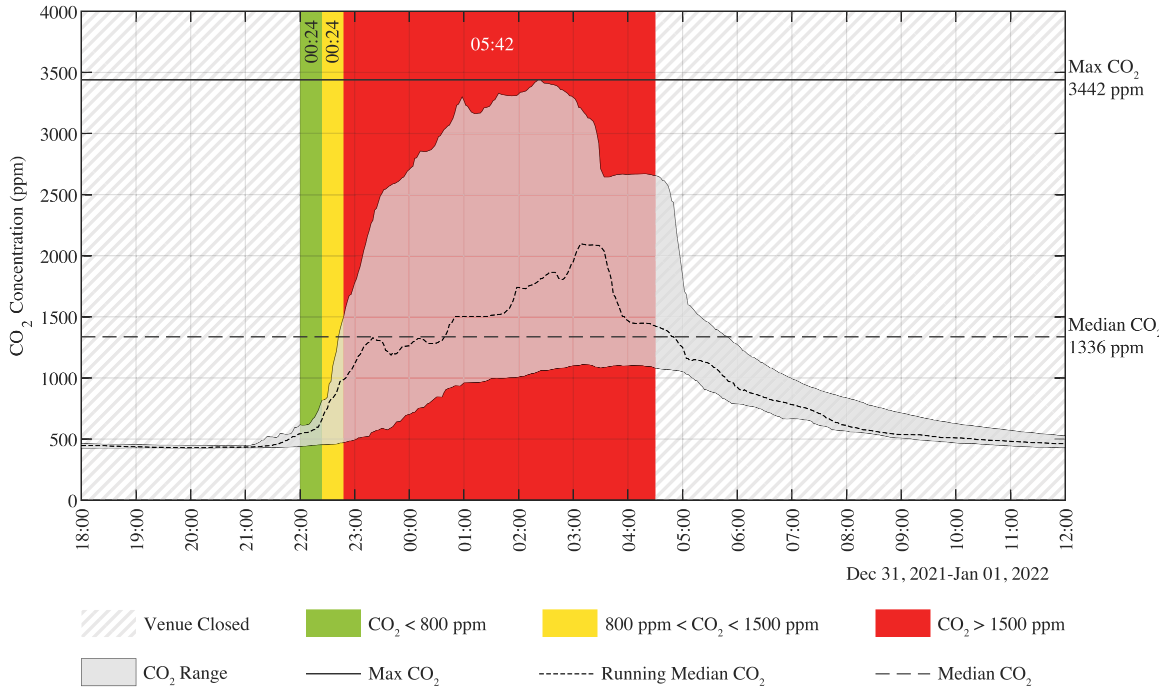

Fig. 1. Example CO_2 monitoring data from the nine CO_2 monitors of venue 5 N demonstrating the four CO_2 metrics presented in Section 2.1.1. The time noted at the top of the highlighted sections indicates durations at the associated CO_2 concentration. [Full Page Width: 190 × 110 mm].

identifiable. A summary of these metrics for all Phase 1 venues is presented in Table 4. In the following analysis the CO_2 levels are assumed to be representative of ventilation performance, where a volume flow rate per person is considered.

The presented example demonstrates that whilst the max CO_2 readings can be in excess of 3000 ppm, these readings are often localised to specific areas of a venue (Fig. 1). At the incidence of the max CO_2 value (02:22), the running median CO_2 value was 1794 ppm and the minimum recorded CO_2 value was 1053 ppm. On average, conditions within the venue continued to worsen after this point until 03:08, after which the running median CO_2 value began to decline consistently. During the venue's opening hours, CO_2 values remained below 800 ppm for 7.3 % of the time and were between 800 ppm and 1500 ppm for the same proportion of time. CO_2 values exceeded 1500 ppm for 85.5 % of the time. This suggests that the ventilation strategies of this venue were not adequate despite the venue operating at a reduced occupancy. The remaining nightclub venues exhibited similar ventilation performance (Table 4).

Table 4
Summary of phase 1 venues CO_2 concentration monitoring metrics. All values are determined during venue opening hours.

Venue Type	Venue ID	Maximum CO_2	Median CO_2	CO_2 > 800 ppm	CO_2 > 1500 ppm
		(ppm)	(ppm)	(% of opening hours)	(% of opening hours)
Restaurants	1 R	1938	569	16.8	3.7
	8 R	2323	885	64.4	6.1
	9 R	1509	729	43.4	0.1
	11 R	1255	526	4.9	0.0
	12 R	2705	685	28.6	2.5
	13 R	971	571	2.3	0.0
	19 R	1486	642	22.5	0.0
Cafés	2 C	1990	692	36.2	4.7
	3 C	1932	785	47.9	5.0
	14 C	1342	718	34.8	0.0
Bars	4B	2987	1042	85.1	18.8
	10B	3825	998	67.0	28.1
	15B	3952	497	11.3	1.4
	17B	1755	627	10.8	0.2
	20B	2855	685	42.5	15.9
	21B	2842	618	26.26	7.1
Nightclubs	5 N	3442	1336	83.5	44.3
	6 N	> 10000	1803	82.5	56.6
	16 N	8090	794	49.7	21.0

The summary metrics of Table 4 provide a useful overview of the ventilation performance of each venue. However, a more continuous analysis of the monitored CO_2 data can provide more detailed insight into the venues' ventilation performance during opening hours. Fig. 2 presents the probability of exceedance for CO_2 concentrations in all of the 19 Phase 1 venues grouped by venue type. Visual inspection of the data highlights the consistency of poor ventilation in nightclub venues compared to restaurants, cafes, and the majority of bars.

The probability of exceedance is observed to be variable within each venue type owing to variations in opening hours, occupancy, and ventilation practices. It is worth noting that although the study ensured that a typical 'busy' day occurred during the period of observation, some venues, in particular restaurants and also some nightclubs, were running at a lower capacity than pre-pandemic. By considering Fig. 2 with the venue characteristics presented in Table 1, these observed differences in ventilation performance can be explained. Amongst the restaurants, venue 8 R has the worst ventilation performance. This is a combination of the small venue size (44.1 m^2) and only having natural ventilation (Table 1). Conversely, venue 11 R had the best ventilation performance despite also only having natural ventilation, but the venue was 98 % larger than 8 R. Venue 9 R had the most complex mix of ventilation practices (Table 1) yet experienced reasonably poor ventilation, unsurprising as the natural ventilation was only from a doorway and the wall-mounted fan did not work. The air purifier may reduce the volume of infectious material in the air, however the venue owner had no awareness of the maintenance requirements so any benefit would reduce over the longer term.

Venue 3 C is the only café that had old wall-mounted fans and limited opportunities for natural ventilation (only the doors, which were rarely opened for ventilation due to drafts) which results in the least satisfactory ventilation performance. Venues 2 C and 14 C both have

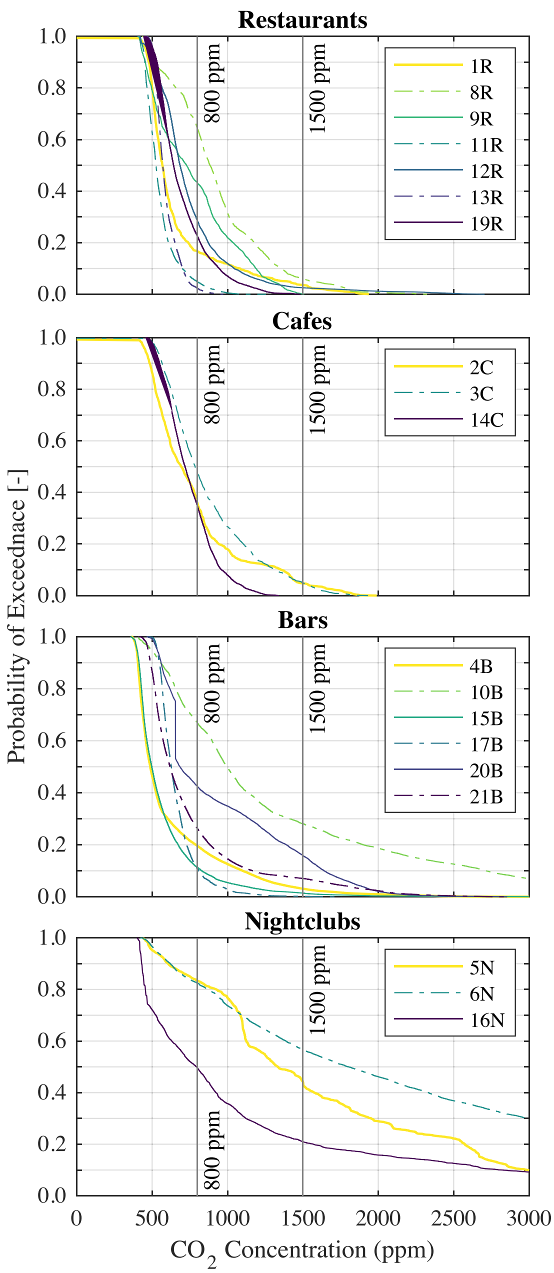

Fig. 2. Probability of exceedance for CO_2 monitoring data during venue opening hours.[Single Column Width: 90x200 mm].

centralised mechanical ventilation, yet there is a stark contrast in the ventilation performance of these venues above 800 ppm. These differences may arise from the contrasting size of the venues, with 2 C representing the smallest café and 14 C the largest.

The ventilation performance of bars in this study are clustered by ventilation type. Venues 15B and 17B show good levels of ventilation performance, particularly above 800 ppm. These venues utilise centralised mechanical ventilation. Venues 4B and 21B effectively utilise natural ventilation to provide a slightly reduced ventilation performance compared to venues 15B and 17B. Venues 20B and 10B do not make effective use of their installed ventilation technologies (natural ventilation and wall-mounted fans) which results in the poorest ventilation performance of the monitored bars.

All nightclubs had centralised air handling units but struggled to provide required levels of outside air per person. The venue with the lowest maximum reading (5 N) appeared to have a regular maintenance regime.

The type of ventilation installed in a venue has been demonstrated to significantly affect its ventilation performance. Typically, those venues with maintained centralised mechanical ventilation provide better ventilation performance than venues with natural ventilation or wall-mounted fans. However, this is not always consistent and to determine opportunities for improvement it is necessary to understand the owners' experiences with the ventilation and their capability, opportunity and motivations to improve ventilation.

3.1.3. Interview outcomes

Several themes were conceptualised from the thematic analysis of interviews with venue owners and managers, organised within three superordinate categories related to the COM-B domains: (1) A basic understanding of ventilation; (2) Limited opportunities to improve ventilation; and (3) Ventilation is not a top priority. A selection of illustrative quotes supports the narrative summary of thematic analysis results that follow. Some quotes have been edited where appropriate to improve clarity, but no changes have been made to their original meaning. Each quote is linked to the anonymous participant and venue code from Table 4, along with a code to specify the occupational category of each participant: O = Owner, M = Manager.

3.1.4. Theme 1: A basic understanding of ventilation

Most participants reported a basic understanding of ventilation. They were aware that ventilation involved the use of extractor fans, opening doors or windows, or using mechanical ventilation systems. Almost all participants identified that ventilation was a means of limiting the transmission of airborne viruses such as COVID-19 by reducing the concentration of virus particles.

"…having an exchange of air really reduces the risk of picking it [COVID] up." **19 R/20B-M**

Several participants with natural ventilation in their venue reported using their senses to know whether ventilation was working. Some reported that opening doors or windows and feeling a breeze through the building gave them confidence that their venue was well-ventilated. Participants with ventilation assisted by wall-mounted fans also reported that they could hear or see their fans working.

"I can see sort of bits moving in front of them, so I know they are pulling out air". **3C-O**

Conversely, participants with mechanical ventilation systems reported having less awareness of these systems and whether they were working effectively. This was primarily due to other people being responsible for controlling or maintaining them.

"Turn it on and it does its job for me really… we get it serviced by somebody every three months so they deal with all that sort of stuff." **5N-M**

3.1.5. Theme 2: Limited opportunities to improve ventilation

Participants described having limited opportunities to improve ventilation in their venues due to a lack of suitable guidance, limited means of natural or mechanical ventilation and an inability to install or upgrade ventilation due to a lack of funds or authority to modify infrastructure.

3.1.6. Sub-theme 2.1: insufficient guidance

Around half of participants reported that they could not recall receiving any guidance on ventilation. Among venue owners and managers who reported that they had seen some form of ventilation guidance, most had received it from government sources or the city council. However, this guidance was frequently described as being too vague to implement.

"apart from saying open doors or open windows, there wasn't a vast amount of guidance I could find that said other practical ways or anything" **15B-M**

Two participants already using CO_2 monitors in their venues reported seeing guidance relating to CO_2 levels. However, one restaurant owner reported that there were inconsistencies in the CO_2 levels that had been recommended.

"some suggested 1500 and some suggested 1000 [ppm]" **12R-O**

Both of these participants also reported that there was no guidance on what to do if they exceeded recommended CO_2 levels.

"within two or three hours we were exceeding that limit. But there wasn't any guidance on what do you do then, you know, once you're exceeding." **16N-M**

3.1.7. Sub-theme 2.2: inability to make changes to the building

Many participants described how their building was not optimised for ventilation in some way. Most of these participants cited a lack of natural ventilation, including no windows, no openable windows or doors, or insufficient wall-mounted fans. Several participants also suggested that their venue would benefit from having a mechanical ventilation system installed or an upgrade of their existing system.

However, most participants identified cost as a significant barrier to installing or upgrading ventilation. Many reported struggling financially since the COVID-19 pandemic. Some participants said they would improve their ventilation if they had the money. Other participants said they would prefer to spend money on improving other aspects of their business.

"if he is given the money to do some improvements for this restaurant he is not thinking about improving the ventilation, he may want to advance the cooking equipment" **13R-O**

Several participants also explained that they could not install or upgrade ventilation in their venue because they did not own the building and it was not their responsibility.

"this is not my building; at the end of the day the structural work is down to [landlord]." **10B-M**

3.1.8. Theme 3: ventilation is not a top priority

Participants tended to prioritise customer comfort and enjoyment over ventilating to reduce COVID-19 risk. Noise complaints and security concerns also deterred the use of natural ventilation strategies.

3.1.9. Sub-theme: 3.1: ensuring customers have a positive experience

Most participants reported using ventilation to maintain customer comfort in their venue. They used it to reduce cooking smells, keep the venue cool in the summer, and prevent the venue from feeling stuffy during busy hours. However, natural ventilation methods in cold weather were not welcomed by customers and were unfeasible to mitigate with heating due to rising energy costs. This generally deterred participants from using natural ventilation or reduced the efficacy of attempts to ventilate their venue in cold conditions.

"If [customers are] cold they will close the door, and they will complain if they're cold. They won't put a coat on. They're in an indoor venue." **4B-M**

All nightclub and several bar managers also highlighted that ventilation was often not conducive to creating the desired atmosphere in their venue. In particular, they reported that ventilation interfered with their use of smoke machines and lighting. Meeting customers' expectations regarding the atmosphere at music events was viewed as more important than ventilation.

"If you'd have had it totally air-con clean air it would have not felt right, if that makes sense…People wanted a sweaty kind of punky show for want of a better word and you've kind of got to do that." **6N-M**

While many participants felt ventilation was not important to most customers due to diminishing perceptions of COVID-19 risk, a minority believed that ensuring good ventilation would help customers feel safer and more likely to visit their venue. These participants used a range of approaches to permit ventilation in cold weather conditions, such as providing people with blankets. However, customer satisfaction typically remained a priority.

"it's balancing the fact that you're trying to give people a really good time, [but] you're trying to make those people who are cautious feel safe." **12R-O**

3.1.10. Sub-theme 3.2: protecting the business from external threats

Several participants from nightclubs, bars, and gyms identified that noise pollution could be a barrier to opening doors and windows in their venue, especially if they were situated close to residential buildings. Some bar managers had mitigated this issue by soundproofing and negotiating their license restrictions. However, another bar manager indicated that noise complaints were currently threatening the continuity of their business.

"that puts our license at risk… So definitely ventilation's not really high on the agenda, and if anything it's probably been put at a detriment as well because we're having to do a few other things to reduce noise bleeding from the building." **21B-M**

Several participants also indicated that security issues prevented them from having doors or windows open. Participants from nightclubs described how leaving extra doors open presented a risk of people sneaking into the venue during events. Participants from restaurants described the risk of theft as a reason they did not leave doors open or have openable windows in their venue.

"We used to have windows but then during the pandemic time we got broken into so many times we had to board it up." ***1R-M***

3.2. Phase 2: creation of guidance material to improve ventilation in hospitality venues

In response to the co-creation workshops, the behaviour change intervention (Fig. 3) took the form of an infographic, containing guidance on improving ventilation in winter for venues that currently have natural ventilation or wall-mounted extract fans only. Venues with ducted mechanical systems were not considered in this study because the Phase 1 surveys showed these venues would require substantial investment to change their systems. Further owners reported a lack of control over the larger ventilation systems in the interviews. The infographic consisted of a motivational component alongside practical guidance on improving ventilation in the short-, medium-, and long-term. The motivational component included information on how improving ventilation could help to reduce respiratory infection risk and staff sick leave. The short-term guidance promoted the use of natural ventilation strategies such as opening doors and windows, including specific advice on how to minimise the impact on thermal comfort.

The medium-term guidance suggested the use of CO_2 monitors and air cleaners, emphasising that CO_2 monitors could help to ensure energy-efficient ventilation and air cleaners could help to improve air quality where noise prevented openings. These suggestions were generated in response to Phase 1 where it was observed that some naturally ventilated venues were at times over ventilating and could potentially reduce heat loss with the use of CO_2 monitors. Conversely, in other venues, improving ventilation would require significant investment and time meaning air cleaners were the only medium-term solution.

The long-term guidance suggested the installation of mechanical ventilation systems including suggestions for wall mounted fans as Phase 1 walk around surveys observed that the scale, and building restrictions on many venues indicated this would be the most cost-effective solution. The infographic also included typical costs and links to more detailed information and recommendations regarding the use of CO_2 monitors, air cleaners, and mechanical ventilation systems. A full-size version of the infographic is available in Supplementary Material S6.

3.3. Phase 3: observations of behaviour and ventilation practice pre- and post-guidance intervention

3.3.1. CO_2 and ventilation practice monitoring

Six venues completed the behaviour diaries necessary to observe changes in ventilation practices from the pre-intervention period (week 1) and the post-intervention period (week 2). This data is summarised in

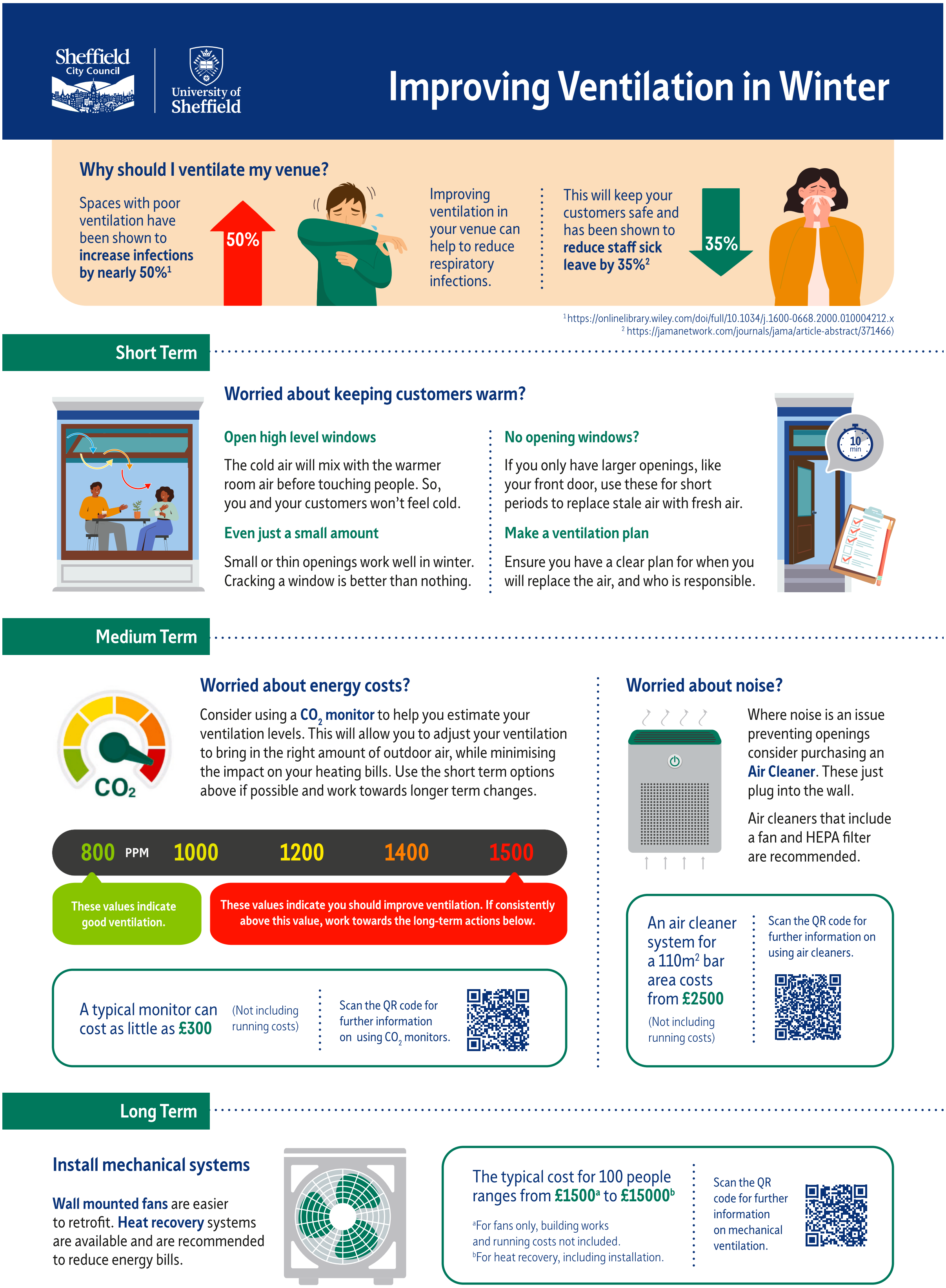

Fig. 3. The Infographic Guidance Document. Inset citations [1]Milton et al. [36], [2]Brundage et al. [37].[Full Page Width: 190x268 mm].

Table 5 as a percentage of each venue's opening hours and is presented alongside the four CO_2 monitoring metrics.

Venue 24 C was the most engaged study participant, increasing the use of all three ventilation strategies by up to 550 % for external door opening. Hence, there are observable changes in the profile of CO_2 concentrations during opening hours (Fig. 4a), with clear instances of when corrective action was taken to reduce CO_2 concentrations within the venue across multiple days (sharp declines in CO_2 concentration and

Table 5
Summary of phase 3 venues CO_2 concentration monitoring metrics and ventilation practices. All values are determined during venue opening hours.

Venue ID	Maximum CO_2 (ppm)		Median CO_2 (ppm)		CO_2 > 800 ppm (% of opening hours)		CO_2 > 1500 ppm (% of opening hours)		Window Opening (% of opening hours)		External Door Opening (% of opening hours)		Wall Mounted Extract Use (% of opening hours)	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
22 R†,‡	1276	1089	620	539	13.7	6.7	0	0	-	-	-	-	-	-
23 R	2780	3748	1150	1169	71.1	68.5	29.6	37.0	0	0	19	10	0	0
24 C	2121	2163	1404	1218	93.5	93.6	39.5	23.3	0	2	6	33	75	87
25 C†	1942	-	894	-	72.3	-	1.9	-	0	0	0	0	0	0
26B‡	2059	3722	944	1105	67.6	76.8	7.7	21.0	-	-	-	-	-	-
27B	3318	4642	1054	978	67.4	63.1	28.8	28.2	24	28	79	80	0	0
28B	3635	2832	1387	627	79.4	38.5	43.2	20.5	0	0	0	0	0	1
29B‡	2968	3186	1270	1241	77.0	77.1	41.5	39.3	-	-	-	-	-	-
30 L	1431	1258	615	691	29.4	37.7	0	0	0	0	0	0	0	0

† No Post-Intervention data is available.
‡ Ventilation Behaviour Diaries were not completed by these venues.

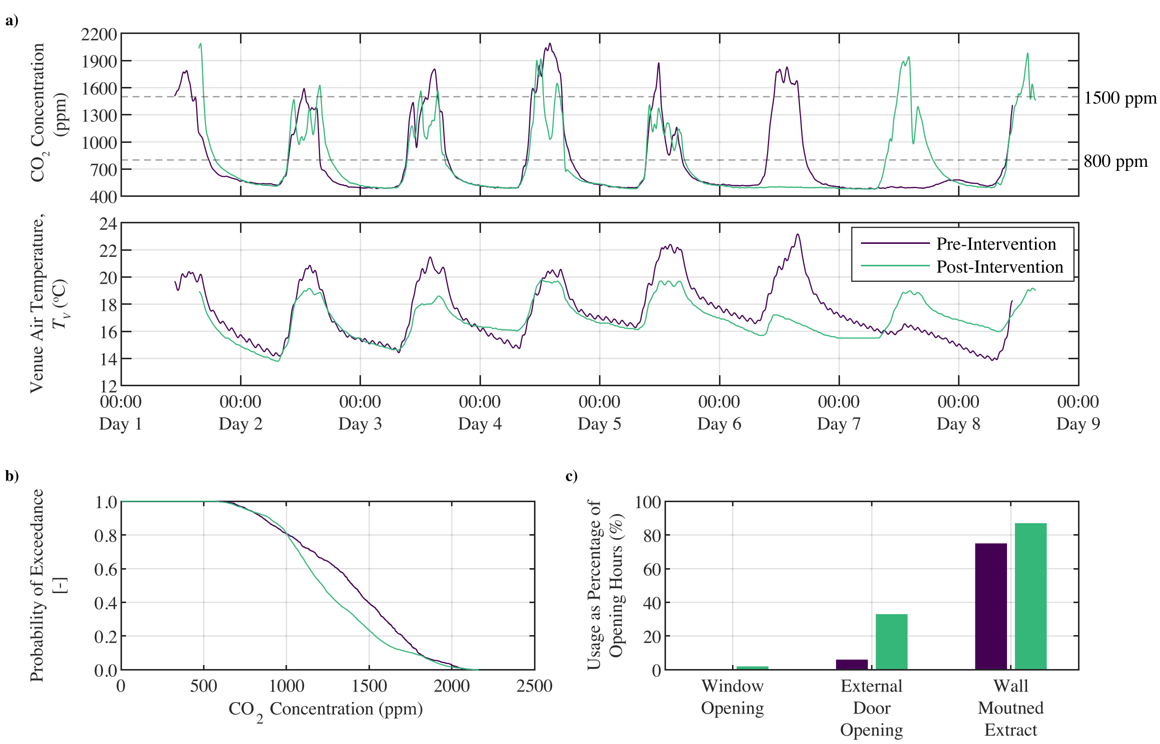

Fig. 4. Phase 3 summary results for venue 24 C. a) Pre- and post-intervention CO_2 concentration and venue air temperature profiles. b) Probability of exceedance for CO_2 concentration during venue opening hours. c) Change in ventilation behaviours as a percentage of venue opening hours.[Full Page Width: 190x120 mm].

reduced venue air temperature in post-intervention data), are attributed to the changes in ventilation practice. These changes in ventilation practice resulted in lower median CO_2 concentration and a reduced time with concentrations above 1500 ppm (Table 5). However, max CO_2 and time above 800 ppm statistics are very similar between the pre- and post-intervention monitoring periods. This phenomenon is also evidenced in the probability of exceedance plot (Fig. 4b): both lines are similar until 1000 ppm before diverging, with post-intervention data showing better ventilation performance, they then converge again at 1800 ppm before reaching similar peak CO_2 values. This data suggests that the ventilation practices were primarily changed in response to the 1500 ppm threshold rather than at 800 ppm. The venue owner described occupancy as typical and similar across the two weeks of the study.

Modest positive changes were made to the passive ventilation practices of venue 27B (door and window opening) in response to the guidance document intervention (Table 5). This resulted in some minimal reductions in the median CO_2 values despite an increase in the maximum recorded CO_2 concentration. Similar modest changes were made to active ventilation practices (wall-mounted extract fans) in venue 28B, but this resulted in more significant reductions in CO_2 concentrations across all metrics. Both venues reported occupancy to be typical across both study weeks. Although lack of detailed occupancy data and external weather data means changes in CO_2 readings cannot be directly attributed to an increase in ventilation, the data do demonstrate the sharp decline in CO_2 readings at times when doors or windows were opened, or fans turned on. Alongside Table 5, which shows an increase in ventilation behaviours in 3 of the 6 venues, this indicates that ventilation is likely to have been improved in some venues by the change in behaviours. The changes in median CO_2 in the other two venues (22 R and 29B) were so small they are within the accuracy of the monitors and these venues did not evidence any changes in behaviour. The remaining three venues (23 R, 26B, 30 L) showed small increases in median CO_2, which are again within the accuracy of the monitors.

3.3.2. Acceptability of infographic intervention

Seven venues completed the acceptability questionnaires before and after the intervention. The results of these questionnaires are summarised in Table 6. Participants were generally positive about the infographic, the short-term actions proposed within it and the medium-term action of using CO_2 monitors. Of the proposed actions, mechanical ventilation had the lowest acceptance due to the larger scale infrastructure changes—and associated financial costs—required for implementation.

3.3.3. Self-reported behaviour change

Seven participants answered questions about behaviour changes that they made or planned to make in the future as a result of the intervention (Table 7). Most participants reported implementing the proposed short-term actions to improve ventilation in their venue and indicated that they are likely to continue doing so in the future. More than half of the participants reported making use of the CO_2 monitors that were provided to them. However, at the conclusion of the trial, less than a third of participants were considering purchasing CO_2 monitors for their venue in the future. A small number of venues indicated they were more likely to purchase air cleaners or mechanical ventilation systems post intervention.

4. Discussion

The Phase 1 study demonstrated that many venues struggled to provide adequate ventilation when at full capacity, with CO_2 values commonly exceeding 800 ppm and for the more crowded venues (bars and nightclubs) exceeding 1500 ppm. The interviews with venue owners in Phase 1 of this research programme explored the perceived barriers and facilitators to using ventilation strategies in hospitality venues. The results of the thematic analysis revealed that most barriers were related to the COM-B [19] domains of social and physical opportunity and reflective motivation. All participants had some methods to deliver outside air to the space (physical opportunity). However, the ventilation technologies of Phase 1 venues were highly varied in their sophistication and condition. Venues with lower occupancy density were able to ventilate using natural ventilation when motivated to do so, with adequate number and size of openings. However similar venues also demonstrated poor ventilation performance. Generally, venues with centralised mechanical ventilation provided better ventilation. The larger, and more crowded venues would not be able to be adequately ventilated naturally. Most had some form of centralised mechanical system but the condition and age of this varied substantially. Many venues clearly did not make full use of wall mounted fans when they were available. In addition, while participants possessed basic knowledge of how to ventilate their venue (psychological capability) Phase 1 participants felt they were unable to use ventilation strategies effectively due to a lack of clear guidance (physical opportunity)

Table 6
Acceptability questionnaire results in response to 'How acceptable was the <topic> to you?" Where a value of 1 was completely unacceptable, 3 is neutral, and 5 is completely acceptable.

Topic	Week 2*	Week 3*	Negative Factors
The infographic	3.7	3.5	Cost of implementation Required operational changes Customer thermal comfort Noise concerns
Short-term actions	4.1	4.1	-
CO_2 monitors	3.9	4.0	Cost of purchasing monitors
Mechanical ventilation	3.3	3.1	Lack of funding for installation Lack of space for equipment Uncertain return on investment Reduced venue ambiance

* See Section 2.1.3 for description of the timeline.

Table 7
Self-reported behaviour change results. Presented as the number of respondents from a total of seven.

	Pre-Intervention	Post-Intervention
Implemented short-term actions	-	5
Likely to implement short-term actions in the future	-	6
Used CO_2 monitors to improve ventilation	-	4
Likely to purchase CO_2 monitors in the future	4	2
Likely to purchase air cleaners in the future	1	3
Likely to purchase mechanical ventilation in the future	0	1

In particular, ventilation strategies appeared to be more challenging to implement compared to other practical COVID measures (e.g., providing hand sanitiser). Participants attempting to improve their use of ventilation strategies, struggled to access specific guidance about what air quality metrics or standards they should be aiming for (physical opportunity). In addition, the variability and a lack of guidance on ventilation technology upgrade paths resulted in participants highlighting practical and financial constraints on installing or upgrading ventilation (physical opportunity) and competing priorities related to running the business (reflective motivation) as barriers to improving ventilation performance. More broadly, effective ventilation was generally not seen as a priority and sometimes conflicted with participants' overarching motivation to provide a positive experience to customers and protect the business (reflective motivation). Notably, concern about maintaining thermal comfort was a commonly reported barrier to using natural ventilation strategies, which is consistent with recent research conducted in hospital [17] and school settings [38]. Ventilation also conflicted with other regulatory requirements related to noise, which would directly affect the continuity of the business by putting licences at risk. Taken together, Phase 1 findings suggest that study participants were aware of the need for ventilation and may be willing to act on relevant guidance, but only if they have appropriate means of ventilation and if using ventilation strategies does not conflict with other business priorities. Although there is substantial ventilation guidance available [32, 39, 40] these do not reflect the challenges identified in this study, and therefore bespoke guidance for the sector is required.

In Phase 2, the barriers and facilitators identified in the Phase 1 interviews were integrated into a guidance infographic (the intervention) through a process of co-design with environmental health officers and hospitality venue owners, managers, and employees. The guidance capitalised on venue owners' basic knowledge of the need to ventilate their venues by providing reinforcing statistics on the impacts of poor ventilation on customer and staff health. The structure of the guidance—from short-term to long-term measures—provided venue owners with a clear technology upgrade pathway and presented clear strategies to overcome the motivational barriers of customer thermal comfort and noise pollution which had been identified as barriers during Phase 1.

In Phase 3, the guidance infographic was favourably received by venue owners with the short- and medium-term guidance having the highest acceptability. Five of the seven study participants reported that they made some attempt to implement the short-term actions of opening windows or doors and having a ventilation plan. However, only three venues reported this behaviour change as part of the ventilation behaviour diaries. Participating venues highlighted no specific prohibitive factors to implementing the short-term actions, but many remained concerned about maintaining customer thermal comfort during the particularly cold weather of the study period. Although not mentioned by the venue owners it is worth bearing in mind that increased ventilation is required when venues are busier. Given venues mentioned difficulties in using the CO_2 monitors alongside busy working operations it may be that they are simply too busy with customers to take the time to increase ventilation.

The deployment of CO_2 monitors into Phase 3 venues, alongside the provision of the guidance infographic, led to increased efforts to ventilate half the venues that completed behaviour diaries. A similar proportion of venues (5 of 9), reported they used the CO_2 monitors to inform their ventilation strategies. However, at the conclusion of the trial, fewer venues were considering purchasing CO_2 monitors (2 vs. 4) to manage ventilation in their venue. Some participating venues highlighted that the specific CO_2 sensor technologies deployed in the study were not simple enough to be integrated into already busy business operations. The likelihood of air cleaner and mechanical ventilation purchases increased over the course of Phase 3 (from 1 to 3 venues), which may have been due to participating venues becoming aware of poor ventilation performance from the CO_2 monitoring and the perceived need for more automated ventilation strategies. A couple of venues (24 C and 30 L) expressed surprise when shown the CO_2 readings as they had assumed their ventilation was okay, this indicates that carrying out short term monitoring may be useful to highlight where issues are present. Given that some venues responded positively to improving their ventilation post intervention it is recommended that CO_2 monitors are deployed during environmental health officer visits, with the results and ventilation guidance shared with the venue owner. For the CO_2 readings to be effective this would need to be during a period of high occupancy, and a period of at least one hour of monitoring is suggested.

4.1. Limitations

This study was carried out relatively rapidly in order to deploy guidance and assist venues with improving their ventilation. The need to undertake the work quickly has led to several limitations in the methods. In particular it should be highlighted that the CO_2 monitoring was designed to be indicative of ventilation performance following the methods of SAGE [7] and Malki-Epshtein [9]. A lack of measurement of outdoor weather, outdoor CO_2 or occupancy, limits the possible analysis and the calculation of flow rates in spaces is not possible. The mounting of sensors higher in the late-night settings may result in larger measurements due to stratification in the space, and is not necessarily representative of the breathing zone. For instance, previous studies have shown differences of up to 200 ppm over 1.5 m [41]. Further, the supplementary material demonstrates a comparison between the different sensor types, which resulted in a maximum difference of 206 ppm.

Despite these limitations the scale of differences shown in Phase 1 (Table 4 and Fig. 2), gives confidence to the stated differences between venue types and need for improvement. In Phase 3 the variation in CO_2 levels before and after intervention is low and there are many confounding variables (e.g. occupancy and weather) that make these results on their own difficult to interpret. More useful is the dynamic behaviour indicating purging (Fig. 4), and the behavioural diaries which demonstrate increased ventilation behaviour for some owners (Table 5).

Despite the limitations, the results clearly highlight the range of ventilation equipment and performance in small scale hospitality venues, and consistent behavioural barriers to improving ventilation. Similarly, while the data set evaluating the effect of the guidance is limited, it does provide evidence that with guidance and CO_2 monitoring, it is possible to increase ventilation - although competing business challenges may prevent this occurring.

Whilst this study was a response to the COVID-19 pandemic, the poor levels of ventilation in the sampled venues demonstrates a need to improve such ventilation to reduce risk of respiratory infections and exposure to other indoor air pollutants. This is particularly important to staff who spend a significant amount of time in these spaces.

5. Conclusions

This study aimed to identify the current state of ventilation performance in small-scale hospitality venues and to provide clear guidance on how to improve ventilation performance where necessary. Short-term continuous CO_2 monitoring identified that in the majority of participating venues, ventilation performance was below recommended standards. Most business owners stated they were not able to improve ventilation due to a lack of clear guidance, lack of money to upgrade systems or responsibility for the building and competing priorities. In these businesses, customer comfort, atmosphere, noise control, and security were of greater importance than improving ventilation.

When hospitality venues were provided with CO_2 monitors and bespoke guidance, 3 of 6 venues increased number of ventilation actions they took, such as opening windows/doors or switching on wall mounted fans. Where business owners were provided with CO_2 monitors, they stated an increased likelihood to purchase air cleaners (2 of 6 increased their interest) or mechanical ventilation equipment (1 of 6 increased their interest) but a reduced likelihood of future CO_2 monitor purchases. These findings highlight the benefit of using short-term monitoring and the developed guidance for businesses to raise awareness of their ventilation levels and opportunities for improvement. This could be carried out as spot checks during high occupancy by Environmental Health officers.

Further work is recommended to assess the impact of the guidance in the longer term, deploying this over a longer period of a year in a larger number of venues. It would also be of benefit to test this in different geographical areas where both climate and culture will influence the results.

CRediT authorship contribution statement

De-Ville Simon: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Pott Sophie:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation. **Wood Chantelle:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Peng Zhangjie:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Farooq M. Zaeem:** Investigation, Data curation. **Blouchou Giota:** Writing – review & editing, Formal analysis. **Suhag Alisha:** Writing – review & editing, Investigation, Formal analysis. **Murphy Edward:** Methodology, Investigation, Conceptualization. **Hathway Abigail:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, 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.

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Dedication

We'd like to take this opportunity to express our gratitude for the input from Eddie Murphy of Ollio Consulting to this project. Eddie unfortunately passed away during the project but whilst involved provided substantial technical input to the project, as well as enthusiasm and support to the researchers.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.indenv.2025.100097.

Data availability

CO_2 data, interview transcripts and venue meta data is available on the Open Science Framework at https://doi.org/10.17605/OSF.IO/Q726R.

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