COVID-19 risk-mitigation in reopening mass cultural events: population-based observational study for the UK Events Research Programme in Liverpool City Region

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ABSTRACT

Objectives: To understand SARS-CoV-2 transmission risks, perceived risks, and the feasibility of risk-mitigations from experimental mass cultural events before COVID-19 restrictions were lifted.

Design: Prospective, population-wide observational study.

Setting: Four events (two nightclubs; outdoor music festival; business conference) open to Liverpool City Region UK residents, requiring a negative lateral flow test (LFT) within the 36 hours before the event, but not requiring social distancing or face-coverings.

Participants: 12,256 individuals attending one or more event between 28th April and 2nd May 2021.

Main outcome measures: SARS-CoV-2 infections detected using audience self-swabbed (5-7 days post-event) PCR tests, with viral genomic analysis of cases, plus linked NHS COVID-19 testing data. Audience experiences were gathered via questionnaires, focus groups and social media. Indoor CO_2 concentrations were monitored.

Results: 12 PCR-positive cases (likely 4 index; 8 primary or secondary), 10 from the nightclubs. Two further cases had positive LFTs but no PCR. 11,896 (97.1%) participants with scanned tickets were matched to a negative pre-event LFT: 4972 (40.6%) returned a PCR within a week. CO_2 concentrations showed areas for improving ventilation at the nightclubs. Population infection rates were low, yet with a concurrent outbreak of >50 linked cases around a local swimming pool without equivalent risk-mitigations. Audience anxiety was low and enjoyment high.

Conclusions: We observed minor SARS-CoV-2 transmission and low perceived risks around events when prevalence was low and risk-mitigations prominent. Partnership between audiences, event organisers and public health services, supported by information systems with real-time linked data can improve health security for mass cultural events.

Key words: COVID-19; mass gatherings; cultural events; SARS-CoV-2 transmission; respiratory virus risk-mitigation.

INTRODUCTION

Governments world-wide restricted mass gatherings in response to the COVID-19 pandemic to reduce severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) transmission.[1] Events such as music festivals, business conferences, and nightclubs are characterised by mixing in close proximity, often in poorly ventilated spaces over long periods. These characteristics have been linked to "super-spreading".[2 3] Limiting the size of gatherings or cancelling events reduced infections.[4 5] Such measures, however, come at a cost to public wellbeing and the economy.

More than a year of cancelled events during 2020-2021 damaged industries that require mass gatherings, with many people losing their livelihoods.[6] In addition, the support of social fabric and mental wellbeing from cultural events was lost. This disproportionally affected younger people, who were last to be vaccinated and hit hardest hit by job-losses and restricted social mixing.[7] As such, some countries experimented with reopening mass events. One randomised controlled trial of attendance at an indoor nightclub in Barcelona with 473 attendees showed no transmission among participants,[8] although levels of risk mitigation included compulsory N95 mask wearing and maximised ventilation, which do not reflect how events can run sustainably. At the Dutch FieldLab experiment (music festival for ~1500 participants in March 2021), the subgroup assigned to mask-wearing tended to take their masks off in the dance tent.[9] Other COVID-19 testing protocols researched at events included regular reverse-transcription polymerase chain reaction (PCR) and rapid antigen testing on the PGA European golf tour,[10 11] which were unaffordable and impractical for many events.

From Summer 2021, the events sector reopened around the world, with temporary returns to lockdowns in some countries and regions. The World Health Organisation issued "Strategy considerations for SARS-CoV-2 and other respiratory viruses in the WHO European Region during autumn and winter 2022/23: protecting the vulnerable with agility, efficiency, and trust".[12] This marked a shift from reduction of transmission en masse to protecting the vulnerable, following evidence of net harms from blanket control measures.[13 14]

We present findings from the UK's Events Research Programme (ERP) response to the COVID-19 pandemic, relevant to future respiratory virus pandemic preparedness and mass cultural events. The ERP was developed to generate evidence on the reopening of events, assessing the risk of SARS-CoV-2 transmission, and to pilot risk-mitigation measures in line with the UK Government's Roadmap for 'reopening' society.[15] The first phase of ERP included nine pilot events with various measures to prevent and contain SARS-CoV-2 transmission.[16] Four of these events took place in Liverpool

between 28th April and 2nd May 2021, including a nightclub (on two consecutive nights), an outdoor music festival with a tented dance area and a business conference. Audiences were invited from residents of Liverpool City Region only, enabling a population-based study of transmission. Attendees required a negative rapid antigen lateral flow test (LFT) at an asymptomatic testing site within 36 hours prior to the event and were encouraged not to attend if they had symptoms. Social distancing and face coverings were not required, thus reflecting how the events sector could reopen sustainably. This study aimed to evaluate SARS-CoV-2 transmission, public and audience experiences, and public health operational requirements for running COVID-19 risk-mitigated events.

METHODS

Study design

Adult residents (18+ years) of Liverpool City Region were invited to express interest in attending one or more test events – via usual advertising and general media communications. Individuals were invited to consent to participate in the ERP and complete a pre-event questionnaire on-line. Those who consented and completed the questionnaire could purchase a ticket and were directed to take a rapid SARS-CoV-2 antigen LFT[17] at a supervised asymptomatic testing centre within the 36 hours before the event, and not to attend if they had any symptoms listed on Government/NHS websites. Positive test results were reviewed by the local public health team, who then contacted individuals to inform them to self-isolate and not attend. Close contacts of test-positive individuals were traced and asked to test and not to attend any test events. Tickets were cancelled and refunded for those testing positive. Participants were given two swabs at the pre-event, asymptomatic testing centre, to return for PCR testing: one on the day of the event, and one five days post-event. Following the event, participants were asked to complete another questionnaire. Consent was obtained to link participant details to routinely collected NHS data to identify any PCRs or LFTs taken by participants pre- or post-event. All attendees of the events were included in the study.

Data were collected in pre-event questionnaires on attitudes to the test events. Individuals were asked their age, address, sex and ethnicity, and if they were concerned about catching and/or transmitting COVID-19 at the event. Post-event questionnaires captured attitudes towards COVID-19 certification, including vaccine passports, as a requirement for attending future events.

Data linkage

Participants gave consent for linkage of their questionnaire responses and ticket data to NHS and administrative records. Residential address was linked to Index of Multiple Deprivation (2019) at Lower-Layer Super Output Area.[18] COVID-19 testing and vaccination data were linked via the NHS Combined Intelligence for Population Health Action (CIPHA) system.[19] CIPHA provided near real-time (updated every 30 minutes) NHS Test & Trace results and vaccination status, and has supported COVID-19 responses and national studies previously.[17 20] We linked participants' consent records, survey data, and ticket information to NHS data within CIPHA using fuzzy matching based on name, postcode and date of birth, to look up NHS number for test result matching. We used this system to validate tickets (as holder test-negative) and gather study data including age, sex, address, COVID-19 LFT and PCR test results (including previous positive results in 2021), genomic analysis of positive cases, and vaccination status.

The University of Liverpool Research Ethics Committee approved the study (Approval 8486, 25 Nov 2020: amended 31 Mar 2021) before commencement.

Classification of cases

Attendees were classified as potential index cases if they had a positive PCR swab in the 24 hours before, or up to 72 hours after, the start of the event, using home-test kits handed out at pre-event testing centres. Those with positive PCR swab results from four to seven days post-event were classified as possible primary (infected by index case at the event) or secondary cases (infected by primary case after the event). A probabilistic classification tool was also used, adjudicated by experts in relevant viral dynamics (Appendix 2 P1).

Statistical Analyses

Analyses were carried out on pseudonymised data, those undertaking analyses did not have access to person identifiable information.

All participants who attended any event were included in the study cohort. Descriptive statistics on attendees of each event, and overall, were generated. Multiple logistic regression was used to identify factors associated with the likelihood of returning a PCR test within 7 days after event. Models were fitted per event and overall. Statistical analyses were carried out in R (version 3.6.1 or later). Details in Appendix 2 P1.

Additional data collection and analysis

The ERP at Liverpool incorporated a wide range of quantitative and qualitative research methods, data collection and analyses. Genomic analysis was performed using civet 3.0 (Cluster Investigation and Virus Epidemiology Tool https://github.com/artic-network/civet) with CLIMB background genomic data for the relevant time periods generated by the COG-UK consortium. Indoor venue air CO_2 concentrations were measured as a proxy for exposure to exhaled breath at two venues (nightclub and conference centre) (Appendix 2 P2). Eight focus groups were run with attendees (Appendix 2 P2) and media reports and social media posts were examined (Appendix 2 P3-6). Public health intelligence systems were used to examine COVID-19 outbreaks within 2 weeks before/after the ERP events.

Role of the funding source

This evaluation was commissioned via the UK Government's Department for Digital, Culture, Media and Sport (DCMS) as part of ERP and used the UK Government's Department of Health & Social Care Test & Trace infrastructure. The University of Liverpool independently analysed the study data and reported the findings to DCMS.

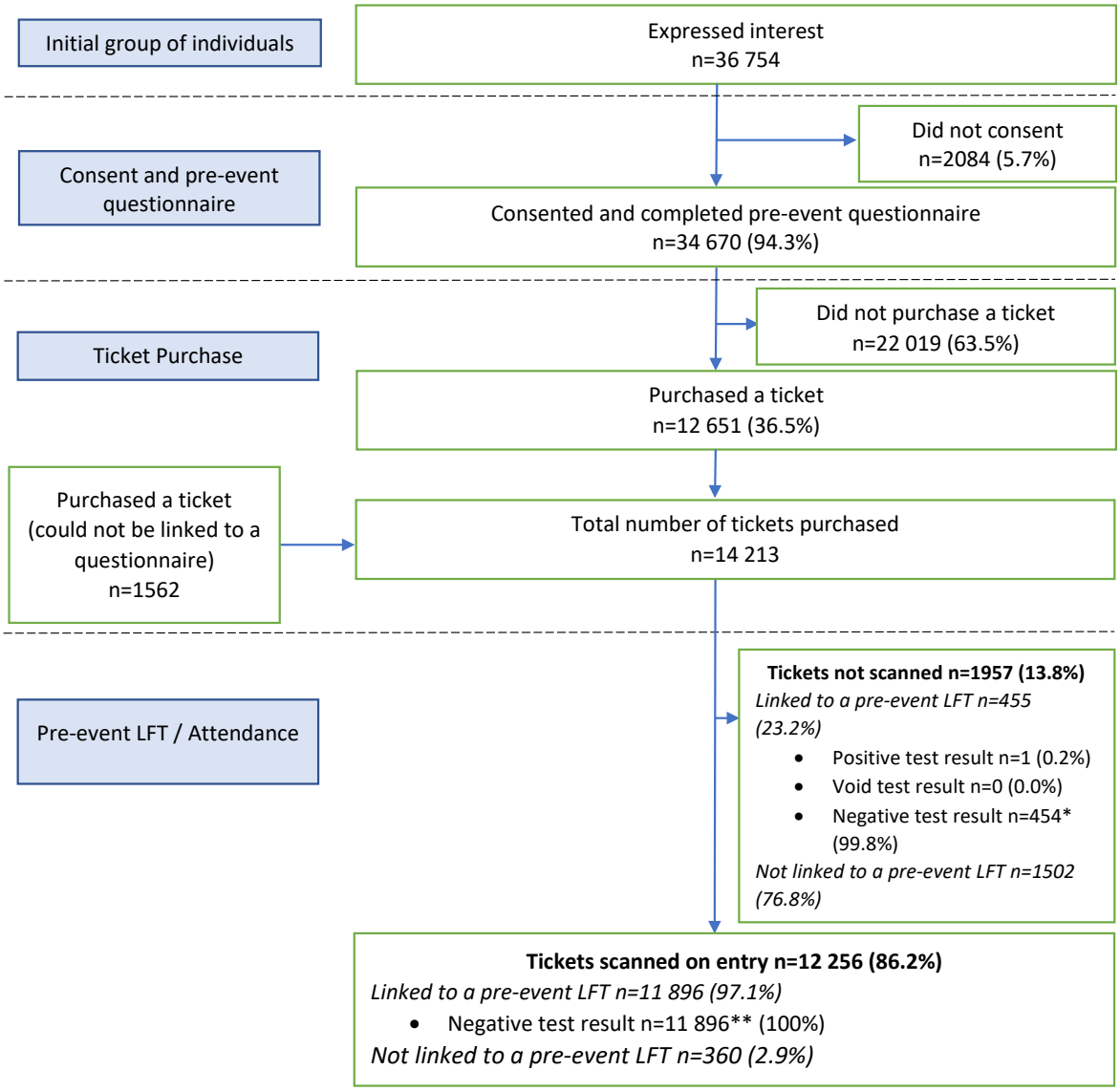
RESULTS

36,754 individuals expressed interest in attending the events. 34,670 (94·3%) consented to take part and completed a pre-event questionnaire, of which 12,651 (36·5%) purchased a ticket. 1562 tickets could not be linked to a pre-event questionnaire, so were acquired outside the main booking system. 12,256 individuals (86%; 12,256/14,213) were recorded as entering one or more events, with a total of 13,262 attendances. 8% of people attended multiple events. Overall flow diagrams pre-and post-event are shown in Figures 1 and 2, with diagrams for individual events in Appendix 1.

Demographic characteristics of attendees are in Table 1. Participants were largely young (with older, more likely vaccinated attendees at the business conference) and predominantly from white ethnic backgrounds and deprived areas. Attendees of the nightclub and music festival resided in areas with younger and student populations (Appendix 3, P1). Vaccination rates among attendees were low, as most younger people had not yet been offered a vaccine.

Full descriptive statistics of questionnaire responses are shown in Appendix 6.

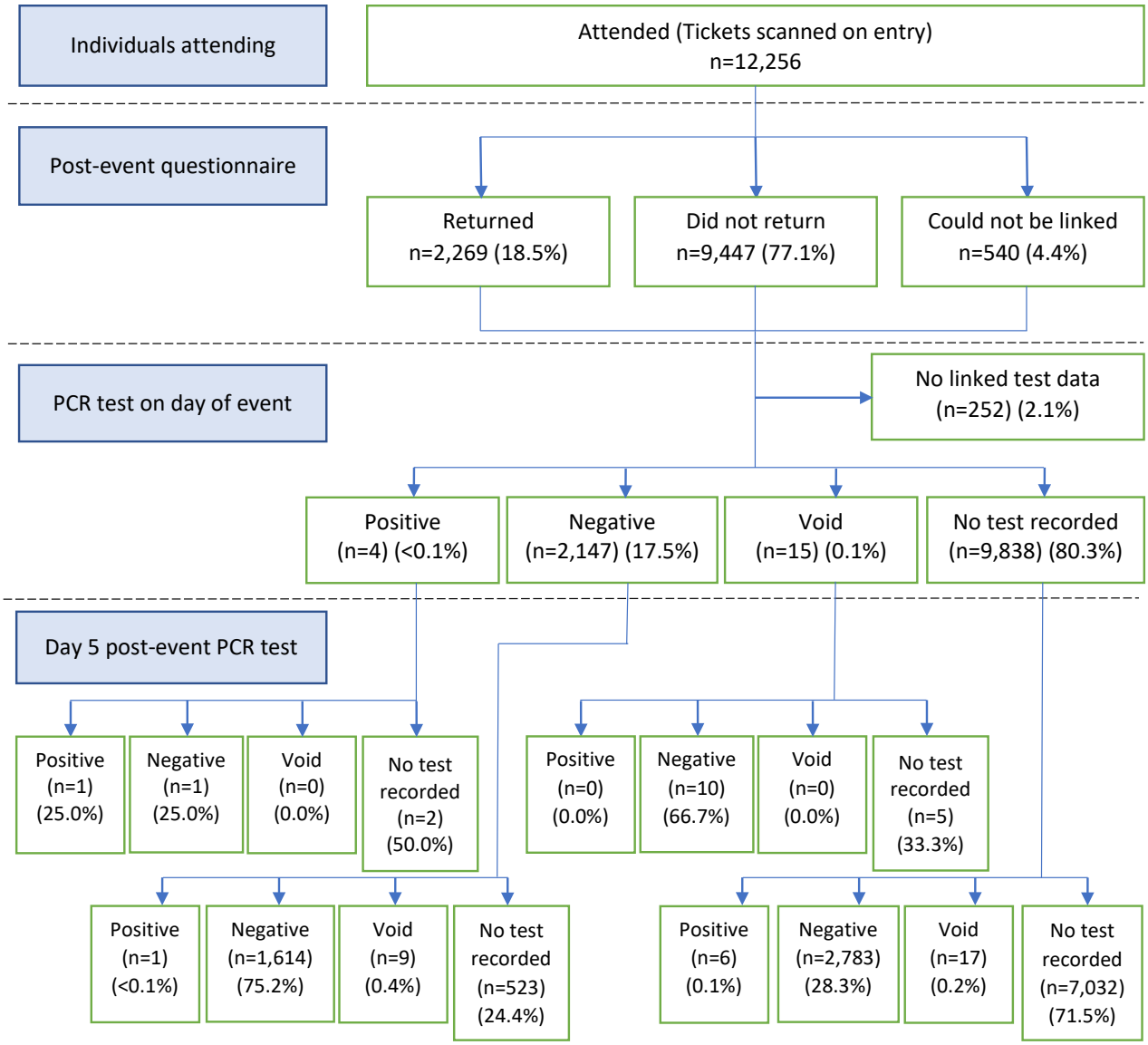
Figure 1: Pre-event participant flow diagram for all events combined.



* 3 of these 454 were preceded by a positive LFT (one of which also had a void LFT) and 1 was preceded by a void LFT.

** 1 of these 11 896 was preceded by a positive LFT and 20 were preceded by a void LFT.

Figure 2: Post-event participant flow diagram for all events combined.



Note: One positive case is not included, as they were not scanned on entry to the event but reported that they did attend.

Table 1. Descriptive statistics of the characteristics of people who attended the Liverpool events

Characteristic	All events n= 12 256	Nightclub x2 n = 6802	Music festival n = 6101	Conference n= 149
Age (Median, IQR)	21 (19,25)	20 (19, 23)	22 (20, 27)	44 (33, 51)
n missing	79	39	40	0
Sex				
Female	5982 (50·0%)	3232 (48·7%)	3159 (52·8%)	77 (52·7%)
Male	5991 (50·0%)	3410 (51·3%)	2822 (47·2%)	69 (47·3%)
Missing data	283	160	120	3
Ethnicity				
White	10 701 (89·3%)	5857 (88·1%)	5,455 (91·1%)	107 (73·3%)
Another ethnic group	32 (0·3%)	21 (0·3%)	12 (0·2%)	1 (0·7%)
Asian or Asian British	228 (1·9%)	156 (2·3%)	93 (1·6%)	3 (2·1%)
Black or Black British	73 (0·6%)	56 (0·8%)	15 (0·3%)	2 (1·4%)
Mixed ethnicity	296 (2·5%)	191 (2·9%)	126 (2·1%)	3 (2·1%)
Prefer not to say	654 (5·5%)	368 (5·5%)	284 (4·7%)	30 (20·5%)
Missing data	272	153	116	3
IMD Quintile[2]				
1 (Most deprived)	4234 (36·4%)	2280 (35·3%)	2088 (35·8%)	44 (31·9%)
2	2828 (24·3%)	1682 (26·0%)	1345 (23·0%)	24 (17·4%)
3	2702 (23·2%)	1525 (23·6%)	1465 (25·1%)	26 (18·9%)
4	1202 (10·3%)	575 (8·9%)	645 (11·0%)	30 (21·7%)
5 (Least deprived)	681 (5·8%)	400 (6·2%)	297 (5·1%)	14 (10·1%)
Missing data	609	340	261	11
Vaccinated				
No	9002 (73·7%)	5346 (78·9%)	4174 (68·5%)	50 (33·8%)
Yes	3215 (26·3%)	1427 (21·1%)	1918 (31·5%)	98 (66·2%)
Missing data	39	29	9	1
Had SARS-CoV-2 in 2021				
No	11 193 (95·0%)	6267 (95·5%)	5579 (94·9%)	133 (96·4%)
Yes	590 (5·0%)	296 (4·5%)	299 (5·1%)	5 (3·6%)
Missing data	473	239	223	11
Returned PCR within 7 days				
No	7032 (58·6%)	4506 (67·7%)	2925 (48·8%)	64 (43·8%)
Yes	4972 (41·4%)	2149 (32·3%)	3074 (51·2%)	82 (56·2%)
Missing data	252	147	102	3
Concern at infecting others				
Some concern	5786 (51·0%)	2941 (48·3%)	3142 (53·7%)	85 (57·4%)
Not at all concerned	5568 (49·0%)	3145 (51·7%)	2706 (46·3%)	63 (42·6%)
Missing data	902	716	253	1
Vaccination passport				
Opposed	329 (16·1%)	160 (20·2%)	172 (13·5%)	4 (11·8%)
Indifferent or in favour	1712 (83·9%)	631 (79·8%)	1106 (86·5%)	30 (88·2%)
Missing data	10215	6011	4823	115

[1]Kruskal-Wallis test for age, Pearson's chi-squared test for categorical variables; [2]Index of Multiple Deprivation (IMD) quintiles are based on national reference.

Of the 12,256 attendees with tickets scanned, 11,896 (97%) could be matched to a pre-event LFT, all of which were negative. For 360 attendees (3%) no pre-event LFT data could be linked (Appendix 1).

Table 2 describes attendees who had a positive PCR test in the pre- or post-event windows. Of 12,256 attendees, 2151 (18%) were matched to a non-void PCR test result in the first window (days 0 to 3). Four of these PCRs were positive and regarded as potential index cases (0·2%). A total of 4416 (36%) of attendances could be matched to a non-void PCR test result in the second window (days 4 to 7). Eight of these tests were positive (0·2%). Of these, one had already tested positive in the first window. The remaining seven were regarded as potential primary or secondary cases. One additional positive test in the second window was found from a ticketholder who did not have their ticket scanned, but reported attendance, giving a total of 8 likely primary or secondary cases. 1617 (13%) of attendances had non-void PCR test results in both time windows.

Of the 12 cases described above, one potential index case (#4 in Table 2), and two likely secondary cases (#8; #10) were identified from symptomatic PCR tests carried out at NHS testing centres. The remaining nine cases came from return of research PCR swabs issued pre-event. Although the Delta variant was starting to spread in the population from which the audience was drawn, where virus genome data was available, three of five cases from the Friday nightclub, all six cases from the Saturday nightclub and two cases from the music festival, showed S-gene target-failure, indicating infection with the Alpha variant that was most prevalent in the community.

Further examination of LFT and PCR results taken outside the pre- and post-event windows identified three additional potential index cases (#13-15).

Table 2: Potential index cases (day 0-3) and likely primary or secondary cases (day 4-7) identified from positive PCR tests

Event	Case number	Estimated day of swab (day of event=day 0)	Ct value	Variant (C=confirmed, P=probable)[1]	Notes	Likely classification using Ct values and contact tracing info[2]
Potential index cases from PCR tests days 0-3						
Music festival	1	Day 3	32	Alpha (P)	Also tested positive 18 days before event	Low-index
Nightclub (Friday)	2	Day 0	33	Alpha (P)	Also tested negative on day 1	Unrelated
Nightclub (Friday)	3	Day 0	21	Alpha (P)		High-index
Nightclub (Saturday)	4	Day 2	22	Alpha (C)	Further positive tests on days 7, 9 and 16	Low-index
Likely primary or secondary cases from PCR tests days 4-7						
Music festival	5	Day 6	33	Alpha (P)		High-index or secondary
Nightclub (Friday)	6	Day 5	26	Delta (C)		Primary
Nightclub (Friday)	7	Day 5	32	Alpha (P)		High-index or secondary
Nightclub (Friday)	8	Day 5	20	Delta (C)		Primary
Nightclub (Saturday)	9	Day 5	24	Alpha (C)	Further positive test on day 7	Secondary or unrelated
Nightclub (Saturday)	10	Day 7	18	Alpha (C)	Further positive test on day 9	Primary
Nightclub (Saturday)	11	Day 5	13	Alpha (C)		Primary
Nightclub (Saturday)	12	Day 7	15	Alpha (C)		Primary
Additional potential index cases from positive LFTs						
Music festival	13	Day -1	N/A	Unknown	Both positive and negative LFTs the day before the event	High-index
Music festival	14	Day 1	N/A	Unknown	Positive LFT, no PCRs matched	High-index
Additional potential index cases from PCR test outside testing window						
Nightclub (Saturday)	15	Day -8	13	Alpha (C)	Negative LFT the day before the event	Low-index

[1] C=confirmed variant from genomic sequencing, P=probable variant based on whether S-gene target was detected

[2] Index cases would arrive at the event already infected (sub-categorised into high and low viral load), primary cases would be infected at the event by an index case, secondary cases would be infected by a primary case after the event, unrelated cases would be infected by someone not at the event.

One inclusion criterion was that attendees should not have received a positive PCR result in the thirty days prior to the event. We did not cross-check this with NHS records prior to admission. A total of 10 ticketholders with positive PCR tests in the prior 30 days attended events (Appendix 3 P4, all showed a negative pre-event LFT). One tested positive 8 days before attending (#15) and the remaining 9 tested positive more than 2 weeks before the event.

Two ticketholders with positive LFTs prior to the event, were subsequently scanned into the event (Appendix 3, P5). One had a positive LFT three days pre-event but received negative results from both a PCR and a second LFT prior to attending. The other received a positive result, then went to a different test centre later the same day for a second test, which was negative (#13).

Eight attendees had a positive LFT result within a week after attending events (Appendix 3, P5), of whom 2 (#8 and #10) had a concordant positive PCR (either from ERP issued tests, or NHS symptomatic testing sites), 5 had discordant PCR within 7 days, and one had no PCR test recorded (#14).

A combination of contact-tracing information, PCR (including cycle threshold: Ct) and LFT results and symptoms were used to make more detailed estimates of whether participants were likely to be infectious at the event, have become infected at the events, or have become infected later due to further contact with attendees. The results are shown in the final column of Table 2, with more details in Appendix 3, P2-3.

Viral genomic sequencing was available for eight attendees with positive PCR tests. Two Friday nightclub attendees (who attended together) had confirmed delta variant (#6 and #8) with similar genetic lineage to cases detected from UK surveillance sequencing in the Merseyside area in the same week. One of the two reported symptoms the next day, with family members having been symptomatic pre-event. All six Saturday nightclub attendees with positive PCRs had alpha variant confirmed. Phylogenetic tree analysis grouped five of these together with similar lineage, including a friendship group of four confirmed by contact-tracing (#4, #9, #10 and #12), and a fifth from outside Merseyside (#11). The closest UK surveillance cases on the tree to these were all in Merseyside, suggesting linked community transmission. Further analysis of these five cases showed two distinct genomic groupings, cases #4 and #9, and cases #10, #11 and #12. The sixth case from Saturday was case #15, who had tested positive 8 days pre-event. This attendee was in a distinct catchment from the others, suggesting they were unlikely to be a linked index case. Tree diagrams are shown in Appendix 3, P10-12.

Further positive tests were matched for 67 attendees after post-event follow-up (Appendix 3, P6-7), with final data extract taken on 10th June, corresponding to day 43 for the first event (conference)

and day 39 for the last (outdoor music festival). All participants testing positive after the post-event window were S-gene target positive, indicating infection with the Delta, and not the Alpha variant that was dominant during the events.

Factors associated with PCR test return

Exploratory analysis of factors associated with PCR return indicated that males, younger people, attendees of Black or Black British ethnicity, those who were not fully vaccinated, those who had tested positive for SARS-Cov2 in 2021, and those who expressed no concern about infecting others at the event had lower comparative odds of returning a PCR swab. Individuals attending the music festival, which offered an incentive to return PCR tests, had higher odds. Details in Appendix 3 P8.

Indoor venue air CO_2 analysis

Analysis of indoor venue CO_2 concentrations showed acceptable or good ventilation at the business event, but high variation at the nightclub events indicating localised areas of poor ventilation and crowding associated with high occupancy close to the stage. Details in Appendix 4 P1-2.

Focus groups

Some apprehension was expressed prior to the events over fear of transmitting SARS-CoV-2 to other people. Some participants expressed initial uncertainty and anxiety about ticket issuing linked to a negative test result. The transition away from social distancing was received very well:

> *"And I was quite anxious before going to the event that I would find it very uncomfortable to be in an environment with so many people. It's gone from nothing to all, if you like, in the space of half an hour. But amazingly, I felt completely safe".*

Others expressed that abandoning social distancing measures and not wearing masks felt strange at first, although once inside the venue, behaviour reverted rapidly to non-socially-distanced interactions. Despite initial feelings of anxiety for some, all participants quickly reverted to natural pre-COVID socialising.

> *"I did think originally that I might keep my mask on but then when I got in there I thought, 'No, take the mask off, I don't feel that I need this.' I should add, I have had my first jab because I'm a lot older than most of the people probably there, so I had had one jab which also made me feel a bit more comfortable, but I felt safe".*

At the conference, an area had been set aside for those wanting to socially distance, but this was not used.

Social distancing was reported as impossible at the egress from the music festival due to large numbers preferring to keep in groups, despite guidance not to.

Most participants felt safe at events, and this was clearly associated with the requirement to have a negative test prior to attendance. In addition, vaccinated participants reported feeling safe due to immunisation. Some anxiety about unvaccinated people attending future events was expressed.

Digital and social media analysis

367 media articles from 15 April to 15 June 2021 were examined. Computational sentiment and qualitative analyses showed the Liverpool ERP was endorsed and promoted through official channels. Sentiment scores were positive and high, with content focused on entertainment aspects. However, an analysis of 4,282 comments posted in response to the media articles showed public reactions were polarized, which was also reflected in the sentiment scores ranging from extremely positive to negative, averaging as a neutral score. Analysis of 2,144 public Tweets (including 831 retweets) showed a diverse range of views over the events or associated publicity, and the average sentiment score was positive.

Discussions about falsifying LFTs were found in a small number of Tweets (38), with a negative sentiment indicating disapproval of this behaviour. Public comments (1320) condemned six TikTok videos over practising with test kits to fake negative results, especially regarding wastage of kits. By contrast, 2500 comments on 50 TikTok videos showing how to fake positive results ranged from amusement to condemnation, again focusing concern on waste of kits.

Further detail is in Appendix 4.

Concurrent outbreaks and clusters of cases

The 7-day rolling rate of new cases in Liverpool on the first day of the events was 13·6 per 100,000 population.[21] Data on outbreaks and clusters in Liverpool City Region concurrent with events identified several foci of linked cases, including one super-spreading event associated with a swimming pool with more than 50 linked cases, which did not have the ERP risk-mitigations.

DISCUSSION

We present the first population-based evidence of actual and perceived risks of SARS-CoV-2 transmission around the early reopening of mass events before COVID-19 restrictions were lifted. To our knowledge, this is the only evidence of its kind internationally.

The people of Liverpool City Region were invited to attend four experimental events in April and May 2021 as part of the UK's Events Research Programme (ERP). Of the 12,256 individuals attending one or more events over five days, there were 15 linked cases detected through research, public health and clinical testing using population-wide linked data. Half of the cases were likely primary or secondary, reflecting transmission no higher than the background rate, in contrast to a concurrent outbreak of more than 50 linked cases associated with a local swimming pool.

Audiences were free to mix without face-coverings, at a time when mass gatherings were banned, and face-coverings were required at smaller gatherings. Risk-mitigations included: requirement to test negative for SARS-CoV-2 antigen in the 36 hours pre-event; prompt contact tracing including real-time linked ticketing and testing data; and repeated communications asking audiences to minimise contacts in the week before/after the event, to take usual precautions in travelling to/from the event and not to attend if experiencing any official COVID-19 symptoms.

Participant concerns over SARS-CoV-2 transmission risks declined during and after events, and enjoyment levels were high. There was relatively little (16%) opposition to the potential introduction of "vaccine passports" for future mass gatherings, although the response rate was low (17%), and non-responders may have been more opposed. This contrasted with some social media posts opposing any certification, especially vaccine passports. Before the events, some organisers and researchers received threats citing opposition to COVID-19 certification, with one prospective event pulling out. Public sentiments on digital and social media were polarised between strong support for reopening of events and concern over it being "too early". Tweeted sentiments were largely positive, as was media coverage.

Incentivisation and good communication may have led to participation in optional post-event testing being higher than at most other ERP events.[16] An event (Music Festival) offering incentives, outside national ERP protocol, showed higher test returns, although other event-specific factors may have influenced this.

The key strengths of this study are its population-wide design and the realistic way the events were run. Liverpool was the first city in the world to introduce voluntary open-access asymptomatic testing, and has used real-time linked data systems to study patterns of SARS-CoV-2 transmission

and coordinate public health responses since November 2020.[20 22] Liverpool's NHS and public health intelligence system (www.cipha.nhs.uk) was extended to incorporate ticketing and questionnaire data with consent. A mixed methods approach enabled consideration of a broad range of demographic, behavioural, and attitudinal factors affecting participant's experiences.

Over a third of Liverpool's economy is linked to events, visitors and hospitality,[23] and strong existing relationships between event organisers, local authority events and public health teams enabled venues and operations to be stood up quickly and realistically. Mask wearing has been identified as unsustainable by the UK Department of Health & Social Care Project Encore, which became ERP.

There were some limitations. Postal return of PCR swabs was low, although the linked data systems captured all NHS and public health service COVID-19 test (symptomatic and asymptomatic) results in the study population, with over 98% of participants being matched to NHS number, ensuring identification of registered test results. Some cases could have been missed, particularly if infected participants were asymptomatic, did not return a research PCR or were symptomatic and did not seek an NHS test. This means that our data are likely to underestimate transmission risk at the events. We did not aim accurately to quantify SARS-CoV-2 transmission, but to use all available data to detect any major outbreaks. These data were sufficient to detect a concurrent unrelated outbreak in the study population. This suggests that any significant outbreak linked to the events would have been detected in our data. Data-linkage between tickets and test results was incomplete, but very high (98%) relative to other ERP events,[16] and available before the start of the events enabling preventive outreach to ticketholders and their contacts. Participant demographics were associated with likelihood of returning tests, indicating that population characteristics should be considered when planning events with similar mitigations.

Missing data potentially limited our analyses. Linkage across NHS, public health and participant questionnaire records worked well in most cases, but failed in some, for example with misspelt personal details in questionnaire registration and ticket booking. Sensitivity analyses of the logistic models of variables associated with returning PCR swabs, using multiple imputation, show no substantive differences from the complete case analysis. This analysis assumes data are missing at random. This assumption may not hold, as it is plausible that missingness may be explained by unmeasured variables. However, this analysis combined with the relatively small levels of missingness in the included variables (all had less than 7.5% missingness, with most under 5%) offers reassurance that our presented analysis does not lead to biased estimates.

Operationally, automatic cancellation of tickets upon linkage of a positive test result was challenging. To deploy this nationally would require a standard protocol for linking ticketholder

identity to test results, and for this to be adopted between ticketing and public health agencies. Withdrawal of tickets for positive test results needs to consider not only the most recent result but all positive LFT and PCR results within a reasonable window. We found some evidence of 'gaming' whereby a recipient of a positive test result would seek a negative result through further testing. Two of these cases were identified, one of whom attended an event. This was an important practical lesson that eagerness to attend an event may override social responsibility to self-isolate. This could be addressed through app-based tickets that become cancelled immutably on any positive test. Although most non-scanned tickets are likely to be from ticketholders who did not attend, we found evidence that a small number of individuals entered events without tickets being scanned, including one person who later tested positive, identified through contact-tracing. Although this research used testing centres, we found social media posts encouraging eventgoers to report negative home LFT results without taking the test to have a 'certificate' to gain entry. Other ERP events relied on self-reported test results. Developers of testing systems around events should consider further checks such as AI reading of uploaded, single-use QR coded lateral flow device images.

Few studies have been published investigating SARS-CoV-2 transmission at and around mass cultural events. A randomised trial at a Barcelona[8] nightclub showed low levels of transmission with concerted risk-mitigation, like Liverpool ERP, however, both studies were conducted at times of low COVID-19 prevalence. The Barcelona study required mask wearing, which is not sustainable, as shown in a similar intervention in the Netherlands.[9]

We found some evidence that people with symptoms may have attended events, including among likely index cases, with one person reporting symptoms the day after the event, with members of their household already symptomatic pre-event. Communications advising people to stay away from events if they had COVID-19 symptoms should have advised them not to attend if feeling unwell for *any* reason, given changing case definitions[24] and variable perception of relevant symptoms.

We found that 49% of participants were not concerned with infecting others at events, having recently had a negative LFT result. These data were supported by focus groups revealing how people felt at ease following a negative LFT result. Event organisers and public health teams faced balancing reassurance to support event attendance and reinforcement of risk-reducing behaviours. The rapid sale of tickets, questionnaire responses and focus groups indicated general eagerness to attend events, but with inconsistent perceptions of risks and risk-mitigation responsibilities.

Pandemic management around mass gatherings may benefit from building risk communication and prevention information into booking and attendance preparation processes. Pre-event supervised testing is an opportunity to inform eventgoers about risks and mitigations, including post-test

probabilities of infectiousness despite a negative test. Assessment of ventilation at venues using CO_2 monitors may also improve risk-mitigations.

Close partnership between audiences, event organisers, public health services, and real-time, accessible information systems, are key to infection prevention and control around mass gatherings. In pandemics with prolonged restrictions on mass gatherings, as experienced with COVID-19, the economic and social harms from restrictions must be balanced with the benefits of reduced pathogen amplification and acquisition. Optimal risk mitigation needs closer attention to communication and audience-driven processes alongside the time-sensitive nature of pre-event tests and enhanced environmental measures at venues. These lessons apply not only to the COVID-19 pandemic and each variant wave, but also to wider respiratory virus risk-mitigation at mass events in an increasingly connected world, where such mitigations are becoming easier to deploy.

Author Contributions

IB conceived the project and led evaluation. GB led analysis and drafting of the manuscript. IB and MGF led editing of the manuscript. GL and RK led data linkage and digital workflows. CC, DH, KT, MGF, MGS, IB and MG supported data analysis and interpretation. MH led questionnaire construction, deployment and analysis. KOH and EM led digital and social media analysis, assisted by ECa. EC and MA led public health operations and interpreted contact tracing information. RC, DF and NK led focus groups and qualitative analysis. AC, WJE and SM advised on assignment of cases to transmission groups and MGS and JD gave clinical and virological advice. MB and TF led the NHS Test & Trace input to the project. LME, MCo and BR performed air quality monitoring and analysis. Linkage with viral genomic data was facilitated by MCh, with viral genomic analysis carried out by EG and KH. AD contributed to interpretation of viral genomic data analysis. All authors commented on the manuscript.

Data sharing

Anonymised datasets are available on request.

Declaration of interests

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Patient and Public Involvement

The experimental events were designed with input from members of the public as part of Liverpool City Council's Public Health, Communications and Culture Liverpool activities. Public Advisers from the National Institute for Health Research Applied Research Collaboration North West Coast advised on the evaluation.

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