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Review Paper

The Skagit County choir COVID-19 outbreak – have we got it wrong?

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ABSTRACT

Objectives: Over time, papers or reports may come to be taken for granted as evidence for some phenomenon. Researchers cite them without critically re-examining findings in the light of subsequent work. This can give rise to misleading or erroneous results and conclusions. We explore whether this has occurred in the widely reported outbreak of SARS-CoV-2 at a rehearsal of the Skagit Valley Chorale in March 2020, where it was assumed, and subsequently asserted uncritically, that the outbreak was due to a single infected person.
Study design: Review of original report and subsequent modelling and interpretations.
Methods: We reviewed and analysed original outbreak data in relation to published data on incubation period, subsequent modelling drawing on the data, and interpretations of transmission characteristics of this incident.
Results: We show it is vanishingly unlikely that this was a single point source outbreak as has been widely claimed and on which modelling has been based.
Conclusion: An unexamined assumption has led to erroneous policy conclusions about the risks of singing, and indoor spaces more generally, and the benefits of increased levels of ventilation. Although never publicly identified, one individual bears the moral burden of knowing what health outcomes have been attributed to their actions. We call for these claims to be re-examined and for greater ethical responsibility in the assumption of a point source in outbreak investigations.

Introduction

A common phenomenon in sociology (and in other disciplines presumably) is that of the 'taken-for-granted reference'. This is typically an original empirical study, the findings of which become accepted and thereafter acknowledged as valid evidence in support of argument or for the generation of new hypotheses or counter hypotheses without presentation of critical re-evaluation.[1]

On March 10, 2020, a community choir in Skagit County, WA gathered for a rehearsal at Mount Vernon Presbyterian Church. On March 17, a member informed the Skagit County Public Health Department (SCPH) that several people had fallen ill. SCPH obtained a list of members and began an investigation on the following day. A report by Hamner et al.[2] was published online on May 12 and in the CDC *Morbidity and Mortality Weekly Report* on May 15. As one of the first such reports for the COVID-19 pandemic, this is well on the way to becoming a taken-for-granted reference, which merely needs to be mentioned as evidence of super-spreading, airborne transmission, and the specific dangers of singing. As of October 14th, 2022, the paper has acquired almost 618,000 views/downloads from the journal Web site, 348 citations in Web of Science, and 772 citations in the wider net cast by Google Scholar. It has also had a major societal impact: "*As a result of this and similar outbreaks, along with mounting uncertainties about modes of transmission, the performing arts industry effectively shut down in 2020.*"[3] Given the paper's early date, however, it is important to review the extent to which its, tentative, proposals of causation have been sustained by subsequent research. If not, there is a substantial risk that further investigations and public policy

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interventions will be inappropriate. This is also a matter of justice and ethics: justice for the unnamed individual identified as the supposed point source of the outbreak and the ethical obligation of scientists to avoid compounding their stigmatization.

We re-examine the original report[2] and additional information,[4] along with the conclusions drawn and the reliance placed upon them by other researchers. We argue that the interpretations placed on the initial report are, in several key respects, unsustainable. We present analysis of the epidemic curve, showing that the outbreak data have been wrongly interpreted, and argue that the distribution of symptom onset is not consistent with a point source superspreader event. Any modelling based on this assumption should be treated with caution and its claimed implications for policy should not go unquestioned.

The report's influence and use

Most works citing the original report[2] simply note it either as an example of the claim that singing rehearsals and performances might spread respiratory infections[5] or as evidence of so-called 'super-spreader' events.[6–9] Such citations are the most basic 'taken for granted' references.

However, some authors have used the report as a foundation for their own work. Bazant and Bush[10] compared the expiratory activities at the event with the respiratory aerosol emissions rate estimates of Miller et al.[4] to develop a model and calibrate a safety guideline. Skagit data have been used for parameter estimation for transmission rates.[11] The estimated secondary attack rate for the rehearsal has been compared with outbreaks in hospitals[12] to calibrate transmission models,[13,14] and to support a claim that transmission is explained by droplets saturating the indoor environment.[15] Other groups have used the Skagit details as an example of SARS-CoV-2 transmission due to environmental factors in buildings,[16] or as a reference point when considering measures for HVAC systems in Japan.[17]

Authors frequently assume that the outbreak started from a point source, a single infected individual. Several modelling studies have used the data and characteristics of the rehearsal space to estimate viral particle concentration or exposure, relying on this assumption. Kolinski and Schneider[18] used the parameters (along with 19 other assumed 'super-spreader' events) to predict a value of viral particle exposure. In modelling infection risk, Lelieveld et al.[19] claim that they match the Skagit infection numbers but also assume a single highly infectious individual. Liu et al.[20] model a physical distancing threshold in indoor environments whilst assuming that the Skagit event was due to a point source. The point source and high secondary attack rate were used to comment on the UK lockdown measures,[21] that the incubation time is as short as two days,[22] or to suggest that if superspreaders could be identified, the virus might be controlled with focused interventions.[23] A model of aerosol transport for natural ventilation[24] claims that the Skagit event demonstrates that the dwell time is likely to be as important as physical distance from the point-source individual, as a measure of infection risk. A spatially explicit agent-based model[25] simulated the outbreak. Although it reproduced the number of infected individuals observed, it was entirely dependent on there being a single infectious individual as the point source.

One of the most substantial and influential papers taking the point source narrative as a given was produced by an international group of engineers seeking to develop a model of factors implicated in aerosol transmission to inform strategies for indoor environmental control:

> "Assuming there is only one index case to account for all transmission and that all transmission was through aerosol is a conservative approach and provides a basis that can be used to develop precautionary mitigation approaches".[4]

This paper has a useful discussion of the three potential transmission routes: direct or indirect contact with fomites; large ballistic droplets travelling directly from one person's nose or mouth to another's; and aerosols. The first two are excluded on grounds that seem persuasive and neither has wider support in the literature on SARS-CoV-2 transmission. However, the authors point to singing as a distinctive source of aerosols, citing both experimental work and other outbreak reports. There is some circularity here: part of the impact of the original Skagit County report has been to stimulate 'me-too' reports about singing that do not replicate its authors' caution.

Having implicated singing, Miller et al. go on to develop their model with the confident declaration that:

> "There is no evidence to suggest that more than one person was infected and showing symptoms at the time of the rehearsal… Assuming that there is only one index case to account for all transmission and that all transmission was through aerosol is a conservative approach and provides a basis that can be used to develop precautionary mitigation approaches."

From the simulation, they conclude that:

> "In the domain of indoor environmental quality control, the first and best measure is generally to minimize indoor emissions. Because it is not yet possible throughout communities to identify individuals who are highly infectious and therefore are potential superspreaders, effective source control cannot be so well practiced, short of suspending large gatherings of high-risk indoor events. Risks would be reduced if fewer people attended, if durations were shorter, and if attendees wore masks."

This translates into a summary of practical implications that group singing indoors should be carefully managed because of the risk of generating large amounts of aerosolized virus and that spaces used for singing should have enhanced ventilation requirements.[4] Taken together, this body of work rests on three main propositions:

1. The space occupied by the choir was poorly ventilated.
2. The choir were engaged in an inherently hazardous activity, i.e., singing.
3. The outbreak was attributable to a single source.

Each of these will be reconsidered in turn using the published text of the outbreak report,[2] with additional material collected by Miller et al.[4]

The rehearsal environment − space, time, and ventilation

The rehearsal took place in linked buildings at the Mount Vernon Presbyterian Church. Fig. 1 shows the complex in plan. For copyright reasons, we are unable to reproduce a Street View image, which can be found at https://google/maps/aNf9kceF5yBSWwLg9. The rehearsal hall is at the right with the breakout space in the main church building on the left. The vehicles give an indication of scale.

The schedule of activities for the 61 attendees is detailed in Table 1. They did not share the same space for the whole time, so that doors were opened and air exchanged, in addition to the operation of the forced air heating system. The main rehearsal

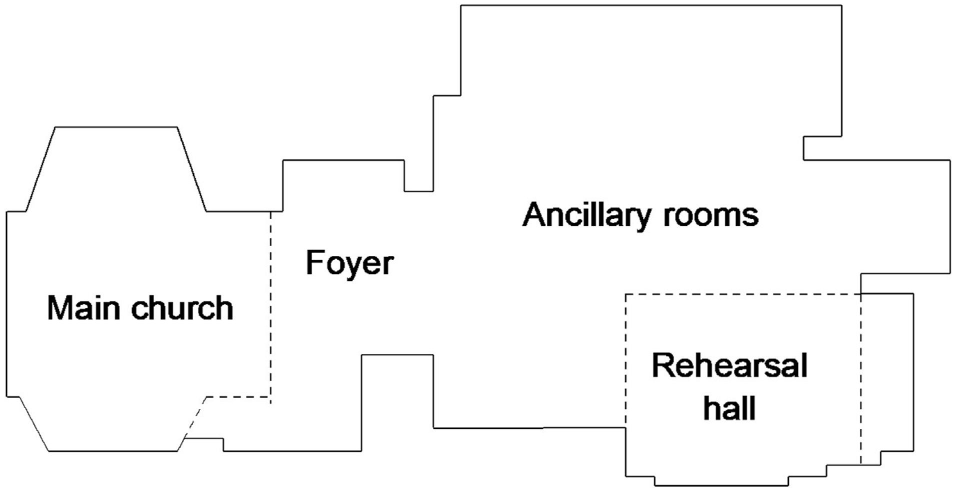

Fig. 1. Approximate plan (not to scale) of the Mount Vernon Presbyterian Church. Derived from Google Earth.

Table 1
Outline of the activities and approximate timings adapted from Miller et al.[4]

Time	Duration (mins)	Activity
6:20	10	Attendees arrive and chat.
6:30	40	All attendees together in the *rehearsal hall*.
7:10	50	Choir splits into two groups: bass/tenor (*main church*) and soprano/alto (*rehearsal hall*) some talking along the way, but not a break.
8:00	15	Break, attendees chatting and having snacks.
8:15	45	All attendees together in the *rehearsal hall*.
9:00		Attendees depart.

room was about 60 × 30 ft, with a vaulted ceiling rising from 10 ft at the sides to about 20 ft at the top. Choir members are reported as sitting in groups scattered across 6 rows of 20 chairs, which would have accommodated a full turn-out of 122 members. The chairs were 6–10 inches apart side-to-side (29.5 in between centers) and the rows were about 55 inches apart. The breakout space was the main church. Its dimensions are not reported but it is said to be capable of seating 150 people. The Street View image shows that its ceiling would rise above that of the rehearsal room and there were only about 20 choir members scattered over the front seats. Neither the rehearsal hall nor the main church can reasonably be described as the sort of densely packed indoor spaces thought to predispose to intensive transmission.

The hazards of singing

Considerable emphasis is placed on the closeness of the chairs, but given the volume of the spaces and the orientation of the chairs, the extent to which participants could have been inhaling each other's exhalations is unclear. For the worst case, if we assume that all 61 people were in the main hall for the 2.5 h period, each with a normal tidal breathing volume of 0.5 l, the choir will consume between 28 and 37 $\times$ 10^3 l h^{-1} representing an approximate usage of 9–11% of the total (assuming no ventilation or other air exchange when doors were opened). The hall's forced air heating system would have generated some air flow but this was turned off when the choir was assembled because an ambient temperature of 68F could be sustained without it. Even if there were only two air changes per hour, the total consumption of air is <5%. Schlieren imaging shows that air exhaled whilst singing is likely to remain within 20 cm of the singer.[26,27] However, being warmer than the surroundings, exhaled air is buoyant.[28] As the choir are stationary for extended periods, we can assume that any exhaled aerosols (light non-settling particles) carrying a viable virus particle will rise in the air column, eventually becoming mixed. The viability of the virus declines rapidly once it leaves the human body[29] so that any descending, cooled, accumulation of particles is unlikely to contain much infective material.

The 'single source'

One choir member was reported to be displaying respiratory symptoms at the rehearsal and has been assumed to be the index case or point source. This person, however, was reported as having very limited interactions with others:

> Choir Spokesperson: *The index case sat [at location X], so no one was in front of [them, within the likely 9 feet landing radius of expired droplets] The person to [their] right was about 5 feet away, and the person to [their] left was about 4 feet away. [They] turned slightly to [one side] to see the director and so [their] exhalations would have been more toward the person on [one side], who [did contract COVID-19]. Our index case went to the bathroom. [They] used the restroom off the hall, not the main restroom. [They did not help with the chairs that evening].*[4]

The report details the activities (Table 1) and the opportunities for interaction as chairs were set up, practice groups formed, and a break where snacks were available. Some members reported consuming snacks, but none reported any physical contact such as hugging. The UK human challenge study[30] shows that it is not easy to induce COVID infection, even under highly controlled conditions.

The original investigation report picks out the theme of super-spreading from a point source:

> Multiple reports have documented events involving superspreading of COVID-19 (2–5); however, few have documented a community-based point-source exposure (5). This cluster of 52 secondary cases of COVID-19 presents a unique opportunity for understanding SARS-CoV-2 transmission following a likely point-source exposure event.[2]

Nevertheless, much of the language used by the SCPH team is highly qualified:

> The 2.5-hour singing practice provided *several opportunities* for droplet and fomite transmission, including members sitting close to one another, sharing snacks, and stacking chairs at the end of the practice. The act of singing, itself, *might* have contributed to transmission through emission of aerosols, which is affected by loudness of vocalization. Certain persons, known as superemitters, who release more aerosol particles during speech than do their peers, *might* have contributed to this and previously reported COVID-19 superspreading events. These data demonstrate the high transmissibility of SARS-CoV-2 and the *possibility* of superemitters contributing to broad transmission in *certain unique activities and circumstances*.[2] [Italics added].

These are speculations not confirmed findings

Is the epidemic curve consistent with a single source?

To test the assertion that the rehearsal was a so-called 'superspreader' event, we compare the observed epidemic curve[2] with contemporaneous modelled incubation periods from other outbreaks. In this way, we examine whether the onset of symptoms for the choir cases was too quick (an abnormally short incubation period), or whether it is more likely that there was not a point source (single person) or common source (event), i.e., the choir members had already been infected in multiple locations by different people. If the likelihood of there being a point source is low, can we then estimate the likely maximum number of cases that were initiated at the rehearsal?

One person had had cold-like symptoms since March 7 and a subsequent PCR gave a positive result for SARS-CoV-2. This individual was considered likely to be the point source. Fifty-two members subsequently became ill, with 32 confirmed as SARS-CoV-2 by PCR testing and the remainder considered as probable cases based on reported symptoms. Symptom onset was reported as beginning on the following day and new cases emerged for up to 12 days. The investigation team chose to focus on the March 7 case as a point source and on the clustering of cases up to March 15, although cases on March 17 and March 22 were included in calculating the median interval to symptom onset as 3 days. This immediately sets up the report's narrative as one of a superspreader event from a point source without first excluding other possibilities.

The point source narrative is, however, not wholly compatible with other findings, particularly that 10 choir members developed symptoms on March 11 and 12, which could indicate that they were infectious as early as March 9. This would be consistent with there being more than one possible source of infection at the event.

The Hamner et al. epidemic curve sets out the dates of symptom onset (confirmed and probable) in choir members with the peak occurring at day three and rapidly falls off. The timing of this peak would be surprising if a point source at the rehearsal were responsible for all of the confirmed and likely cases given the contemporaneous evidence on incubation periods.[31] These estimates have since been confirmed by systematic review.[32] Although Hamner et al. adopted an orthodox assumption in outbreak investigation that there was a point source or index case to be found, they caveated this point.

However, as others disregarded the caveats and took the point source for granted, it is important to examine the timing of symptom onset among these singers and how it compares to the known distribution of incubation periods. The best-fit epidemic curve for contemporaneous data was a Weibull distribution[31]

$$f(x) = \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-(x/\lambda)^k}$$

where k and λ are the shape and scale parameters, respectively. The values of the Weibull shape and scale parameters found by Backer et al. are 3 and 7.2, respectively.[33] The Weibull distribution is appropriate and is likely to yield a good fit because it describes well the lifetime of a component (in engineering terms), i.e., the mean period from first use to failure. In epidemiological terms, this is the period from exposure to infection until the emergence of symptoms. It represents what the likely distribution of infections would be *if a sole person were to be the source.*

The Backer et al. estimate for the mean incubation period is 6.4 days (95% CI, 5.6–7.7) with a standard deviation of 2.3 days (95% CI, 1.7–3.7). In Fig. 2, we plot the Backer et al. estimated distribution of incubation period with the observed epidemic curve. The Weibull curve is plotted as a probability distribution function (the area is unity). The peak in the Hamner et al. epidemic curve is clearly shorter than the typical mean incubation based on wider incubation data. The Hamner et al. epidemic curve peaks at day three, which is more than one standard deviation from what would be expected if the infections had occurred at the rehearsal. Moreover, the rehearsal took place in the evening, pushing the expected distribution later still, i.e., it would be reasonable to start the Weibull curve a day later, further lowering the likelihood of a single person or event being the source. The majority of confirmed and probable cases must have been infected 2–4 days before the day of the rehearsal.

Despite the statistically significant separation of the two peaks, there is overlap. We can devise a method to estimate the likely number of those infected at the rehearsal if we apply the known incubation period (the Weibull PDF) to the choir population. The observed number of infections amongst the choir members is discretised to days, but unfortunately there is insufficient data from the Skagit choir event with which to fit a Weibull distribution. Therefore, the PDF must be discretised. We can find the proportion of the observed number of cases:

$$n_i = f_i \times n_{obs,i}$$

where n_i is the expected number of infections on the ith day, f_i is the proportion of the PDF on the ith day, and $n_{obs,i}$ is the observed number of infections on the ith day. We can estimate the likely maximum total number of infections (N_{attr}), which can be attributed from:

$$N_{attr} = \sum_{i=0}^{25} \frac{k}{\lambda}\left(\frac{i}{\lambda}\right)^{k-1} e^{-(i/\lambda)^k} \times n_{obs,i}$$

This yields a total of four infections, which could be attributed to the rehearsal; it is not meaningful to distinguish between confirmed and probable infections. Furthermore, this is only true if we assume that an index case was responsible for all infections caught at the rehearsal, that everyone was equally exposed to that person, and equally susceptible.

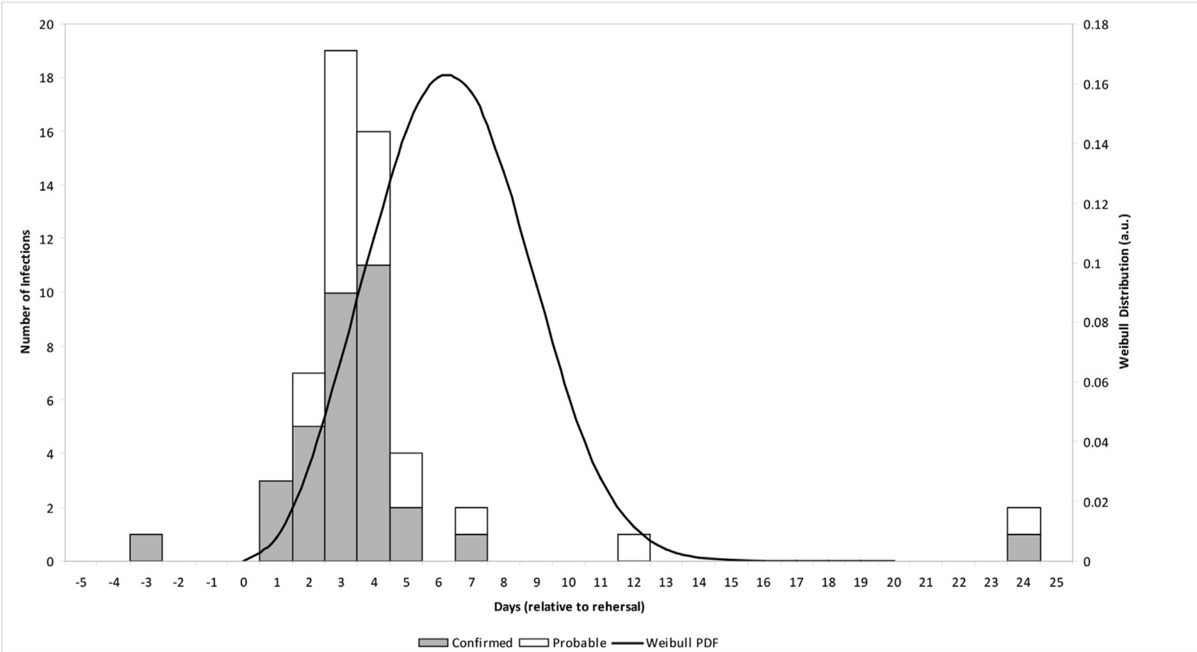

Fig. 2. Plot of the Hamner et al. epidemic curve and the best-fit Weibull distribution for the incubation period contemporaneous with the Skagit choir event. The zeroth day is the rehearsal. The symptoms of the claimed index case started three days before rehearsal.

We are not the only group to express reservations about the use of the Skagit case. Modelling of the venue[34] also suggests that it is more likely that multiple infected people were present, and recognizes that choir members could have been infected before the rehearsal. Whilst it is possible that up to four people were infected from a point source at the rehearsal, it is implausible, based on the timing of symptom onset, that a single individual could be responsible for the 55 confirmed and probable infections amongst the choir members.

Conclusions

This paper is not a criticism of the original outbreak investigation, which was clearly carried out in a professional manner and with appropriate restraint in its conclusions, given the state of knowledge at the time. However, it is clear that many subsequent users of that report have taken its working assumptions and speculative conclusions for granted and built further on them. They have not been treated as hypotheses, to be re-evaluated in the light of the rapid expansion in knowledge and understanding that has taken place since March 2020.

It seems more consistent with the available data to conclude that there were multiple infectious individuals at the rehearsal and that they acquired the infection elsewhere. The mean incubation period is simply too short for it to be plausible that much, if any, infection occurred at the rehearsal. In particular, it is unlikely that transmission occurred through aerosol clouds in the rehearsal hall or main church. There is also a lack of evidence supporting the view that singing played any particular role over and above other kinds of face-to-face interaction within and beyond the rehearsal venue. It is far more likely that community contacts were the main route of transmission. This is consistent with a systematic review by Duval et al.[35] who note the generally low quality of outbreak studies and the lack of genomic testing at the time of the Skagit outbreak. The absence of genomic testing is a serious limitation for most studies claiming to have identified a 'super-spreader' event.

A point-source origin is attractive to disease control specialists as it raises the possibility of a well targeted and highly focused prevention intervention.[23] Multisource introduction[36] and overlapping risks[37] are, however, ubiquitous features of the COVID-19 pandemic.[36,38] Transport, occupational and leisure networks often overlap, and so too do routes of exposure. Failure to recognize this encourages stigmatization of vulnerable occupational and population groups, and of activities that have an important role in supporting well-being.[39,40] The Skagit County Choir outbreak does not provide authority for measures to restrict singing or to require face covering or physical distancing during indoor gatherings at a relatively low density with no special ventilation measures.

Revisiting taken-for-granted papers is important if correct policies are to be adopted. Our first concern here is with the person who has been characterized as the 'single source', albeit not publicly identified, and any emotional harm that may have resulted from appearing to be responsible for deaths and illnesses among their peers. There is a strong ethical obligation on public health scientists to ensure that individuals cannot be stigmatized or otherwise damaged from actions for which they cannot reasonably be held to be culpable. Even anonymous scientific publications are capable of having this impact in a small community, imposing a particular burden of responsibility. While the assumption of a single source may be convenient in outbreak investigations, it must be treated as a starting hypothesis to be tested rather than taken as established fact. To the extent that this outbreak report has been misused as a template, it is likely that other events have been wrongly characterized as single source, that there has been a misconceived search for superspreaders, and a rush to excessive investments in ventilation technologies for enclosed spaces based on models that have assumed what their authors should have questioned. There is also a more general question about the extent to which the literature contains taken-for-granted papers that have not been subject to critical re-examination.

Author statements

Ethical approval

No personal information about any individual was collected in completing this work, therefore no institutional ethical approval was required.

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Competing interests

None declared.

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