Emerging Evidence on COVID-19

Evidence Brief of Size of Gatherings and Characteristics of High Risk Transmission Events

Introduction

What evidence is available on the thresholds or allowable sizes of gatherings or events?

Are there characteristics of gathering events that would make them high risk of transmission of SARS-CoV-2?

This review will address the state of the evidence up to August 18, 2020 with respect to the size of community-based gatherings as well as the characteristics of gatherings that are associated with transmission of SARS-CoV-2. It does not include transmission at home, in congregate living settings (e.g., long-term care facilities, prisons, dormitories) or healthcare organizations, however, it does distinguish social gatherings where people generally do or do not know each other.

Key Points

- Fifty-five studies were identified, including modelling studies, risk assessments, ecological and epidemiologic studies and outbreak reports.
- The studies showed a clear relationship between increased gathering size and risk, but there was not a consistent assessment of different gathering size thresholds (Table 1).
    - An ecological study estimated a 36% reduction in Ro if the cut-off for gathering size was 10 people, compared to 21% if it was 100 people, and a 2% reduction in Ro if the cut-off for gathering size was 1000 people (Brauner et al., 2020). Another study estimated overall 10% reduction in infections associated with gathering size restrictions (Esra et al., 2020).
    - Two models explored thresholds for epidemic collapse, one identified a gathering cut off of 23 people (St-Onge , 2020) and another identified limiting contacts to seven people per 5-day period (Zhao, 2020).
- Several predictive models that employ a network structure were developed to explore the impact of different sizes, types of gatherings and whether they included people that knew each other or did not know each other (Table 1).
    - Small closed community networks (e.g., where groups of people only interact with a chosen group of other people and there is limited interaction outside of that network) were identified as having a low risk of virus introduction. The risk increased with increasing bridges to other networks (e.g., commuting to work in another place, attending a sporting event) (Scott et al., 2020; Sneppen et al., 2020).

  - Random mixing events such as public transit, restaurants/bars and sporting events were high-risk events because people from many small networks mixed and, if transmission occurred could then take the virus back to their network (Scott et al., 2020).
- There were a number of studies that evaluated the risk associated with certain activities:
  - One assessment estimated the relative risk of going to a nightclub was 200-fold higher than eating at a restaurant (Dalton et al., 2020). This was consistent with another study that found >50% attack rate in direct contacts at night clubs (Prakash et al., 2020), a qualitative risk assessment that identified nightclubs, karaoke, restaurant, gymnasiums, ski resorts and cruise ships as high risk gathering settings (Dalton et al., 2020) and a study in Hong Kong found that 30.4% of cases were linked to exposure to bars and bands (Adam et al., 2020).
  - Large gatherings are associated with the largest outbreaks. A carnival in Germany, for example, was associated with 1,700 cases (Walker et al., 2020). Sporting events were associated with approximately 50-100 cases (Leclerc et al., 2020). Small gatherings, such as interactions among household members, had the majority of documented transmission events but usually result in a small number of secondary cases (<5).
  - Other common gathering settings where transmission events were documented included family gatherings (birthday parties, meals etc.), religious gatherings, weddings, social settings, gyms, shopping facilities, shared accommodations and a variety of workplaces from office environments to factory type settings (such as food processing plants).
- Non-pharmaceutical interventions, such as individual hand hygiene practices and community mask wearing and limiting the number of individual contacts, can reduce the risk of a transmission event occurring during gatherings, particularly gatherings of random individuals (Scott et al., 2020).
- Super spreading events (SSEs) have been associated with large gatherings and the following characteristics (Table 3):
  - The index case is often asymptomatic or mildly symptomatic.
  - Several studies have estimated that 10-20% of COVID-19 cases cause ~80% of new infections (Adam et al., 2020; Pozderac et al., 2020, James et al., 2020, Laxminara et al., 2020).
  - The risk of transmission in closed environments is higher than in open-air environments (OR 18.7 (6.0-57.9) (Nishiura et al., 2020).
  - Most transmission events were attributed to the number of close and sustained contact; loud talking, shouting and singing have all been associated with high attack rates.

- These findings need to be considered in light of other individual factors that can affect transmission, such as viral load (Pfefferle et al., 2020) and that some people may have a higher Ro than others e.g., women had a higher Ro than men in Korean clusters (Kim & Jiang, 2020).

Overview of the Evidence

The risk of transmission during gatherings and the relationship of the size of that gathering to the risk of transmission has been directly and indirectly explored in a number of predictive models. Many of the models more directly exploring this question are preprints and still need to undergo the peer-review process. These models are based on scenarios and are parameterized using observational data from the outbreak. The extent to which the findings can be generalized to the local context is variable and should be used with caution.

Published ecological studies estimate the impact of gatherings on the epidemic based on studying the changes in the trajectory of the epidemic after policies to limit gathering sizes were implemented and/or lifted in a region or country. By nature, these studies are at high risk of bias and ecological fallacy.

Estimates of transmission rates and descriptions of SSEs or outbreaks are obtained from data collected during retrospective outbreak investigations, which have a high risk of bias. Thus, these studies are considered to be of low quality and there is a high probability that the conclusion will change as additional evidence becomes available.

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THRESHOLDS FOR GATHERING EVENTS

Eleven agent-based and other network models explore the impact of different restrictions on gatherings and how segmented groups that have minimal random contacts can be protective (Block et al., 2020; Deforche et al., 2020; Kain et al., 2020; Leng et al., 2020; Phillips et al., 2020; Scott et al., 2020; Sneppen et al., 2020; St-Onge et al., 2020; Szapudi, 2020; Weiner et al., 2020; Zhao, 2020). Some of the models explore and explain the concept of small-segmented community networks providing increased protection to an introduction of the virus and the activities that degrade the protection of a segmented network. Activities classified as random gathering events where unknown people mix, such as transportation, commuting to a workplace outside of the segmented network, social places such as bars and restaurants, or sporting events, were considered to degrade the protection afforded by having a segmented community. Other models look at super spreading activities and how the number of contacts in a gathering may lead to a higher number of transmission events. Few studies provided threshold values for gatherings or even explored the implications of different cut offs.

One ecological study reported the impact of gathering size restrictions generally to be a 10% reduction in infections (Esra et al., 2020). Another study estimated a 2% reduction of Ro if the cut-off for different gatherings was 1000 people, compared to 21% if it was 100 people and 36% if it was 10 people (Brauner et al., 2020). Two other models explored thresholds for epidemic collapse, one suggested a gathering cut off of 23 people under one scenario (St-Onge et al., 2020) and another suggested limiting contacts to seven people per 5-day period (P. J. Zhao, 2020).

Two risk assessments evaluate the risk associated with certain activities and try to put individual risk into perspective. The first estimates the risk of transmission was approximately 1 infection per 3,836, (Range: 626 to 31,800) unprotected community-level contacts in the USA on May 31, 2020 (Bhatia & Klausner, 2020). A qualitative risk assessment from Australia describes several high-risk gathering settings and estimates a 200 fold difference in the relative risk of going to a restaurant for dinner versus a nightclub (Dalton et al., 2020). Other settings unpacked in this risk assessment include karaoke clubs, gymnasiums, ski resorts and cruise ships (Dalton et al., 2020).

Given the evidence is primarily predictive models, risk assessments and ecological studies, the extent that the estimates can be generalized beyond the populations and scenarios studied is unknown. It should also be noted that most epidemiological studies on the impact of non-pharmaceutical interventions (NPI's) are not included in this review, as they do not isolate the effect of gathering size restrictions from other NPIs that were implemented almost simultaneously.

Table 1: Thirteen predictive models and risk assessments that explore the impact of gatherings and risk of transmission.

Reference	Study Description	Relevant Outcomes
Predictive Models		
(Phillips et al., 2020) *preprint*	Agent-based model to explore outbreak potential in daycares/schools in Ontario. They explored different ratios of child-educator ratios. The simulations considered 2:8, 3:7, 2:15, 1:15 and 1:30 ratios of teacher to child.	Conclusion: A ratio of 3:7 was most protective and the 2:15 model performed far worse. - Doubling class size from 8 to 15 to 30 doubled the outbreak size. - Drivers of increased risk/impact of larger classes= • higher probability that someone is positive • more students affected when class is quarantined • outbreak size is larger due to a higher number of exposed individuals
(Weiner et al., 2020) *preprint*	Age-of-infection model developed to explore the impact of NPIs on the potential second wave in Illinois. Model starts August 1, 2020. For comparison, Arizona and Florida are also modelled. Data is borrowed from other states already experiencing their second wave e.g., Texas.	- In the two scenarios run, the strict scenario limits on gatherings, closing bars and indoor dining to bring super spreading under control (assuming 80% of cases come from 10-20% of infected people) prevents a second wave.

(Szapudi, 2020) *preprint*	SIR model with modification using a power-law model that allows for inclusion of social connection networks.	- This model shows that by stopping super-spreading events through NPIs, the pandemic is significantly slowed.
(Kain et al., 2020)	SEIR model parameterized for COVID-19 epidemic dynamics by estimating a time-varying transmission rate that incorporates the impact of NPIs that change over time, in five epidemiologically distinct settings:Los Angeles and Santa Clara Counties, California; Seattle (King County), Washington; Atlanta (Dekalb and Fulton Counties), Georgia; and Miami (Miami-Dade County), Florida.	- Effective reproduction number (Re) dropped below 1 rapidly following social distancing orders in mid-March, 2020 - Re started increasing in late May 2020 in LA, Miami, and Atlanta and in June 2020 in Santa Clara and Seattle. - The authors show decreasing the risk of super-spread events (crowded enclosed spaces) is effective.
(Deforche et al., 2020)	SEIR model: Incidence data and deaths in 35 countries (includes Canada) data until mid-May 2020. The authors explore which mobility changes during lockdown were significantly associated with the changes in disease transmission.	- Reductions in individuals using transit and going to work were highly correlated with a reduction in the incidence of COVID-19 in the multi-variable model. - Retail and recreation changes were most significant/ highly associated with Rt changes: Mean reduction of Rt of 0.50 (95% CI 0.18 – 0.81), or an average reduction of 22% (95% CI 8 – 35) in transmission. - Thus, across countries the parameter retail/recreation indicates that venues such as bars, restaurants, malls, mass gatherings provide optimal circumstance for the spread of SARS-CoV-2, as opposed to individual factors.
(Block et al., 2020)	Stochastic Model: Adopting a social network approach, the authors evaluate the effectiveness of three distancing strategies designed to keep the curve flat and aid compliance in a post-lockdown world. They demonstrate that a strategic social network-based reduction of contact strongly enhances the effectiveness of social distancing measures while keeping risks lower.	Three approaches to defining a closed contact network were evaluated to be protective, all of which can be protective if closely adhered to. - Individuals choose their contact partners based on similarity of a predetermined individual characteristic. This facilitates forming small groups e.g., neighbourhood/ small organization. - Individuals consider who their contact partners interact with and do not see people outside of a defined contact network. - Build bubbles through repeat contacts. Individuals decide who they want to interact with. This can be used with work

		units as well. It is difficult for the virus to penetrate these micro-communities.
(Leng et al., 2020) *preprint*	Individual-based model: Using the UK as a case study, a mathematical model was used to assess the effectiveness of various social bubble strategies as part of a gradual lockdown exit strategy.	- Using a base case where non-essential shops and schools are closed, the household attack rate is 20% and Ro=0.8, a number of social bubble strategies are simulated. Results demonstrate that in this base case scenario, social bubbles reduced cases and fatalities by 17% compared to an un-clustered increase of contacts. - Clustering contacts outside the household into exclusive social bubbles is an effective strategy of increasing contacts while limiting some of the associated increase in epidemic risk (e.g., 2 families interact).
(Scott et al., 2020)	Australian agent-based open source model "Covasim". This model allows for contact networks and random/clustered interactions, specifically: households; schools; workplaces; social networks; cafés and restaurants; pubs and bars; public transport; places of worship; professional sport; community sport; beaches; entertainment (cinemas, performing arts venues etc.); national parks; public parks; large events (concerts, festivals, sports games etc.); child care; and aged care.	- The model indicated that the largest risk was re-opening bars and restaurants, followed by workplaces and large events. - Social gatherings <10 were the least risky type of gathering. - The model also implies that it could take more than two months to identify an increase in cases. - The largest risk in a resurgence was allowing individuals to have large contact networks, particularly where there is mixing of individuals who do not know each other. - Random mixing of a large number of people at sporting events for example, is risky because it exposes the individual's smaller, clustered network (home/work/close contacts) to potential introduction of the virus.
(Sneppen & et al., 2020) *preprint*	This agent-based model explored the impact of super-spreading events. In the base model super-spreading events had little effect on the epidemic, however under various intervention strategies, limiting diffuse social contacts – random gathering events - in settings such as bars, transportation, restaurants, parties, concerts and lecture halls is far more effective than limiting the same	- Limiting random gathering events had a large impact on the risk of super spreading events in this model under scenarios where various intervention strategies are implemented.

	amount of contact events in the home and work setting.	
(Zhao, 2020) *preprint*	Social network model: The epidemic is dependant on network connectivity and time to spread. Thus, transmission of the virus is affected by public health interventions such as isolation, quarantine and physical distancing. This social network model explores the level of NPIs needed to contain the COVID-19 pandemic. Contact definition: a spouse, two children, a friend, a neighbor, a colleague, and a cashier during grocery shopping.	- Without social distancing, if a single individual is infected with COVID-19, the average probability that any given person will be infected is 1 in 1.03 million. - After shutting down all non-essential businesses in Italy on March 21, the average number of unique contacts per individual over each viral generation period is expected to be 6.6, leading to a predicted reproductive number of 0.97 - The epidemic in the U.S. can be controlled by limiting the average number of contacts per person to 7 unique individuals over each 5-day period.
(St-Onge et al., 2020) *preprint*	Canadian authors from Laval University provide SIS/SIR models using a network science framework to look at the impact of having structures aka gatherings (groups/ classrooms/ sports teams etc.)	- Demonstrate that localized epidemics can collapse if the group or gathering size remains below a threshold. - The threshold for the mesoscopic localization regime, with a transmission rate $\beta = 0.07$ was 23 people and below.
Risk Assessments		
(Dalton et al., 2020)	This is a qualitative risk assessment on re-opening where they examine the characteristics of retail and recreational situations for high risk of super spreading events. Assumption is that up to 80% of cases may be caused by 10-20% of infected people and some setting characteristics are higher risk than others. Case studies used nightclub and karaoke rooms, gymnasiums, ski resorts, cruise ships, churches and religious gatherings.	- High risk venues should only start to open after low risk venues have been open a sufficient time to know there is no spike in cases. - The relative risk of going to a nightclub is 200 fold higher than eating at a restaurant. - Case study setting characteristics: Nightclubs: 100s of people, close proximity, poor ventilation, social behaviours. Karaoke rooms: 10 people, enclosed room. Gymnasiums: high touch surfaces and increased risk of droplet/aerosol transmission >1.5 meters. Dance/aerobic classes are higher risk where higher respiration rate and movement may be associated with further transmission.

		Ski resorts: unclear Cruise ships: 19 cruise ships had cases prior to March 2020. The design and close contacts allow high attack rates. Screening of crew and passengers is unlikely to prevent COVID-19 cases even in low transmission areas. Churches: Activities include singing and sharing a meal. Several outbreaks have been related to these activities.
(Bhatia et al., 2020)	Risk Assessment: What is the average probability of acquiring COVID-19 infection, being hospitalized, or dying from an unprotected community-level contact in US? Estimates of individual level probability for COVID-19 infection may inform more accurate risk perceptions and facilitate re-engagement with social activity. Among the 100 most populous US Counties, for the week ending May 30, 2020, the median daily case incidence is 5.92 per 100,000, (Range, 0.65 - 35).	- The median probability of COVID-19 infection transmission is 1 infection per 3836, (Range: 626 to 31,800) unprotected (e.g., without social distancing, wearing of masks, hand hygiene, etc.) community-level contact. - For a 50 to 64 year old individual, the estimated median probability of hospitalization is 1 hospitalization per 852,000, (Range: 139,000 to 7,080,000) community level person-contacts and the median probability of a fatality is 1 fatality per 19.1 million, (Range,:3.13 million to 159,000,000 million) community-level person-contacts
Ecological Studies – impact of policies to restrict gatherings on the epidemic		
(Esra et al., 2020) *preprint*	Ecological study: Bayesian model framework to estimate transmission associated with NPIs in 26 countries and 34 US states.	- The estimated overall reduction in infection associated with different NPIs was: • 23% (95% CI: 18-27%) associated with household confinement • 10% (95% CI: 1-18%) with limits on gatherings • 12% (95% CI: 5-19%) with school closures • 17% (95% CI: 6-28%) with mask policies. - 12% (95% CI: 9-15%) overall
(Brauner et al., 2020) *preprint*	Ecological study: Bayesian hierarchical model, by linking non-pharmaceutical interventions (NPI) implementation dates to national case and death counts. Chronological data on NPIs in 41 countries between January and May 2020 was analysed.	Estimate the mean reduction in Ro across the countries for eight NPIs: - Mandating mask-wearing in (some) public spaces (2%; 95% CI: -14%–16%) – this NPI had been implemented after most other NPIs were fully implemented. - Limiting gatherings to:

	Each NPI's effect as a multiplicative (percentage) reduction in the reproduction number R. Many of these were implemented at the same time, however the authors claim their model was able to estimate individual intervention effect due to the large dataset. They present a lengthy sensitivity analysis. Results are averaged across countries, some countries may have had more success than others, this is not reflected in this analysis. (Canada and the USA are not studied)	• 1,000 people or less (2%; 20%–22%), • 100 people or less (21%; 1%–39%), • 10 people or less (36%; 16%–53%), - Closing some high-risk businesses (31%; - 13%–46%), - Closing most nonessential businesses (40%; 22%–55%), - Closing schools and universities (39%; 21%–55%), the model cannot distinguish between these and there may be additive effects such as parents staying home that increases the impact of these NPIs - Issuing stay-at-home orders (18%; 4%–31%).

SIR= susceptible – infected –recovered model, SEIR= susceptible-exposed-infected-recovered, NPI= non-pharmaceutical interventions. Ro= basic reproduction number, Rt= effective reproduction number.

CHARACTERISTICS OF COMMUNITY GATHERING TRANSMISSION EVENTS

Super spreading events (SSEs) or outbreaks include multiple people acquiring infection. Gatherings provide an opportunity for SSEs to occur. By limiting certain high-risk activities and implementing public health measures, including limiting the size of gatherings, the risk of SARS-CoV-2 transmission and the likelihood of super spreading events should be reduced.

Table 2 highlights the importance of controlling super spreaders or SSEs. Retrospective analyses estimate that a large proportion of cases (80%) are due to a small proportion of those infected (10-20%) (Adam et al., 2020; Pozderac et al., 2020; James et al., 2020b; Laxminarayan et al., 2020). One ecological study of North American professional sports reported an association with professional games played early in the epidemic and the number of cases and COVID-19 mortality in that city, which was attributed to large gatherings associated with the game (Wing, Simon, & Carlin, 2020).

Three studies quantify the impact of gathering size restrictions and individual contacts (Jarvis et al., 2020; Scire et al., 2020; Zhang et al., 2020). These studies provide an estimate of the change in behaviour and may help to parameterize or estimate incremental changes in contact patterns that are tolerable at different points in the epidemic.

Table 2: Estimates on the importance of controlling super spreading cases and events.

Reference	Study Description	Relevant Outcomes
Estimates of Impact		

(Wing et al., 2020) *preprint*	Ecological study to compare COVID-19 caseload and mortality between cities that hosted many vs. few NHL, NBA and NCAA games in the first quarter of 2020.	- Found an association with the number of games: • Each NHL or NBA game lead to an additional 783 cases and 52 deaths March - mid-May, 2020. - NCAA games were associated with 31 cases and 2.4 deaths.
(Pozderac & Skinner, 2020) *preprint*	Model to estimate the variation in infectiousness by examining the variation in early-time growth rates of new cases among different subpopulations in the USA.	- Estimates the dispersion of the epidemic and reports that 88% of the case likely were from 10% of the cases.
(A. James et al., 2020b) *preprint*	Analysis of New Zealand's epidemic. COVID-19 cases =1499 Children under 10 were under-represented. Children infected fewer people/ lower secondary attack rate. Asymptomatic cases transmitted to fewer people than clinical cases. Serial interval ~5 days	- Super spreading is a significant contributor to the epidemic dynamics, with 20% of cases among adults responsible for 65-85% of transmission.
(Laxminarayan et al., 2020) *preprint*	This study analyses the epidemiological data from two states in India. Case identification and contact tracing investigations.	- The analysis indicates that 5.4% of cases accounted for 80% of infected contacts.
(Adam et al., 2020) *preprint*	This study analyses the super spreading events in Hong Kong across 135 clusters	- The analysis inferred 20% of infections were responsible for 80% of the transmission events in Hong Kong. - One notable cluster of 106 cases traced to bars and bands accounted for 30.4% of the local transmission early in the epidemic.
Impact of Gathering Restrictions		
(Saidan et al., 2020)	This study calculates context specific Ro based on cluster investigations. This transmission model (SIR) was developed to only model clusters compared and not the entire population.	- Estimated Ro by gathering type • Weddings/ party Ro=5 • Religious gatherings Ro=2.5 • Processing plants (meat) Ro=2.0
(Scire et al., 2020)	Switzerland February 27 - April 22, 2020: Strict gathering rules of <5 people in public places was implemented and self-quarantine for 10 days for anyone with symptoms. Using surveillance data for the number of cases, Ro was calculated for different periods of the epidemic. Sensitivity analysis indicates this result is not an artifact of testing intensity.	- Prior to the gathering restrictions Ro was between 1.5-2. After gathering restrictions were put in place Ro dropped to between 0.6-0.8 in the first third of April 2020.

(Jarvis et al., 2020)	UK survey on contact patterns before and after lockdown. Survey was done the day after lockdown, so it can't really measure longer term adherence.	- 74% reduction in the number of daily contacts (10.8 contacts per day to 2.8). - This would be expected to reduce Ro from 2.6 to 0.62 (95%CI 0.37-0.53) for all types of contacts.
(J. Zhang et al., 2020)	Contact patterns in Wuhan and Shanghai were assessed before and after lockdown using a survey run February 1-10, 2020. 'Contact' was a conversation of three or more words in the presence of another person and/or direct contact.	- Age weighted mean contacts per day was 14.0-18.8 at baseline and reduced to 1.9-2.1 during the outbreak period ($p<0.001$). Overall, contacts during the outbreak mostly occurred at home with household members (94.1% in Wuhan and 78.5% in Shanghai). - The interventions (lockdown) were predicted to block transmission for a Ro before the interventions of 6-7.8.

Table 3 lists repositories of SSEs and outbreaks of COVID-19, studies that investigate the characteristics of these clusters, review literature that summarizes COVID-19 SSEs associated with gatherings and primary epidemiological investigations that implicate gatherings. This list is not exhaustive but describes a wide range of situations under which transmission events have been documented. There are limitations to the research and resources presented in this section including biases that may make some SSEs more likely to be identified and documented. For example, social events are more likely to be recalled than everyday activities and events are more easily traced. Further, some settings may be better represented because they have the infrastructure in place to monitor and identify outbreaks (e.g., prisons or long-term care facilities may have routine monitoring and testing).

Databases of SSEs compiled by researchers and journalists were identified; the most comprehensive one currently has more than 1,400 SSEs documented from the primary and grey literature (Table 3). All include descriptions of the size, setting and other attributes, such as the activity associated with the SSE.

Cluster investigations that estimate the risk of transmission from an infected person or the impact of type of gathering on the size and extent of the transmission event are important to help inform high or low risk situations (Table 3) (Kim et al., 2020; Liu et al., 2020; Pfefferle et al., 2020). These investigations report that a small number of cases may be responsible for the majority of transmission events and that risk of transmission is highly variable. The latter studies are based on retrospective contact tracing investigations, which are at a high risk of bias and may not represent the spectrum of transmission events at gatherings that have occurred. Underreporting of transmission events from gatherings, particularly random mixing events such as public transportation, is highly likely as these events would be difficult to investigate.

General observations across super spreading events (SSEs) that have occurred outside of the household include (Table 3):

- Often the index case was asymptomatic or mildly symptomatic at the time of the transmission event.

- Most SSEs occurred in indoor environments.
- Most are associated with crowded spaces and a prolonged period of time spent in that space or close and intense contact with the infected person (Leclerc, Fuller, Knight, Funk, & Knight, 2020; Swinkels, 2020).
    - Activities such as close range interactions at elderly care homes and events with significant singing, loud conversation or shouting have been associated with SSEs.
- High-risk settings are places where a large number of people congregate. These include large group accommodations, confined working environments, and mass gatherings. (Note household accounts for 50-60%, (Swinkels, 2020)).
    - Approximately 15% of SSEs are associated with entertainment/leisure; dining, sports and fitness, parties, bars and nightclubs.
    - Approximately 5% of SSEs are associated with indoor shopping malls and supermarkets (three SSEs have been associated with outdoor markets).
    - Approximately 3% of SSEs are associated with religious gatherings.
    - Approximately 2% of SSEs are associated with schools.
    - Work environment SSEs (~7%) mostly include office environments followed by food processing plants. Few clusters were associated with working outdoors.
        - Food processing plant outbreaks globally have largely occurred in refrigerated processing environments over other types of facilities. This may be due to the working environment being favourable to SARS-CoV-2 persistence (low temperature and humidity, solid metallic surfaces), work places being crowded and transportation/accommodation being shared, and the workforce being unlikely to not work despite being symptomatic (Chong, Ng, Hori, & et al., 2020; Durand-Moreau et al., 2020).
    - Approximately 7% of SSEs have occurred in shared accommodation such as worker dormitories, prisons, and long-term care facilities.
    - Transportation (~1%) has also been associated with a few clusters including buses, flights and trains.

Table 3: Studies and repositories that summarize the characteristics of gathering events associated with transmission.

Reference	Study Description	Relevant Outcomes
Repositories of COVID-19 Transmission events		
(Swinkels, 2020)	Super Spreading Events Around the World [Google Sheet]. Update version August 15, 2020	- Project includes over 1,400 SSE events. The spreadsheet is available for download and analysis. *The summary*

	- Transmission events with >5 secondary cases are included in this list. - Sources are both primary literature and grey literature. - Details include location, setting, description, indoor, # cases, index date, reference, other settings. - They tag SSEs associated with loud vocalization and those that occur in a refrigeration setting.	*proportions in the text came from this work.* • Currently 21 SSEs are listed from Canada.
(Institute for Investigative Journalism, Concordia, 2020)	Project pandemic A Canadian list of clusters reported across Canada, compiled as a joint initiative of Canadian journalists. *This site is not freely accessible, but is a data repository that is not available elsewhere.*	As of August 18: - 58 food processing plant clusters, the largest was >650 infected - 53 detention facilities have reported clusters.
(Leclerc et al., 2020)	This rapid review and database of SSE events compiled literature up to June 7 2020 and after that, the effort has not been comprehensive. Details include setting, indoor, country, details, reference, date, number of clusters, total cases and attack rates.	SSE Setting / COUNT N=265 / % Building site / 4 / 1.5% Conference / 5 / 1.9% Elderly care / 21 / 7.9% Food processing plant / 21 / 7.9% Funeral / 2 / 0.8% Hospital / 9 / 3.4% Hotel / 3 / 1.1% Household / 38 / 14.3% Shared accommodation / 30 / 11.3% Meal / 17 / 6.4% Party / 14 / 5.3% Prison / 6 / 2.3% Public / 6 / 2.3% Religious / 22 / 8.3% School / 11 / 4.2% Ship / 5 / 1.9% Shipyard / 1 / 0.4% Shopping / 8 / 3.0% Sport / 22 / 8.3% Transport / 1 / 0.4%
Characteristics of Transmission Events and their Association with Gathering		
(Kuebart & Stabler, 2020)	This paper studies SSEs in Germany and considers the socio-spatial spread of SARS-CoV-2 and the drivers associated with spread.	- This article highlights the importance of place, crowd, and activity as facilitators of transmission:

		• A regional outbreak in Western Germany centred on the Heinsberg district (February 2020). • Tourists returning to their home regions while carrying an infection. • Infection networks based on specific focus places or events.
(Kim & Jiang, 2020) *preprint*	This study investigated the properties of the network of cases occurring in Korea. (n=3,127 cases) - Longitudinal transmission network - 147 clusters were identified - 12 had 20 or more cases	- Women had a higher Ro than men. - Older adults (not in long-term care) had higher Ro than young/middle age adults. - Religious gatherings, gyms, long-term care facilities and customer call center caused the longest transmission events.
(On Kwok et al., 2020)	The analysed epidemiological data up to March 3, 2020 from Hong Kong, Japan and Singapore to evaluate the presence and likelihood of clusters or transmission events. The mean cluster sizes were 2.54 (HK), 1.92 (JP) and 3.32 (SG); while the maximum were 16 (HK), 28 (JP) and 31 (SG).	- The probability of observing secondary case clusters of size ≥4 ranged from 10.6% – 21.5% of clusters.
(Adam et al., 2020) *preprint*	This study analyses the super spreading events in Hong Kong across 135 clusters.	- The analysis inferred 20% of infections were responsible for 80% of the transmission events in Hong Kong. - One notable cluster of 106 cases traced to bars and bands accounted for 30.4% of the local transmission early in the epidemic.
(Hamner et al., 2020)	High SARS-CoV-2 Attack Rate Following Exposure at a Choir Practice - Skagit County, Washington, March 2020.	- Among 61 people that attended choir practice on March 10, 2020, the secondary attack rate was 53% among confirmed individuals and 87% among all potential cases. - Singing has been attributed as the cause of the high attack rate.
(Nishiura et al., 2020) *preprint*	This article looks at epidemiological data on 11 clusters of 110 cases total that occurred in Japan as of 26 February: 4 in Tokyo and 1 each in Aichi, Fukuoka, Hokkaido, Ishikawa, Kanagawa and Wakayama prefectures.	- All clusters were associated with indoor environments: gym, restaurant, hospital, and a festival where eating occurred in tents. - This study estimated the odds of transmitting in a closed environment vs. open-air environment was OR 18.7 (95%CI 6.0-57.9). There was no control for confounders or potential interaction with other predictors in this analysis.

(S. Zhao et al., 2020) *preprint*	The analysis of the outbreak on the Diamond Cruise ship, February 2020.	- The dispersion term (k) was estimated to be 44 (95%CI 6-88), which is significantly larger than 1 and implies a lower chance of super-spreading events. In comparison to SARS and other coronaviruses, COVID-19 has less super spreading potential and high potential to persist in a population.
Synthesis of Clusters		
(Leclerc et al., 2020)	Systematic review, search date March 31, 2020, that summarizes 201 transmission clusters.	- Characteristics of clusters: • Indoor or indoor/outdoor settings (21/22). • Large clusters, such as those linked to churches and ships fewer than 100 cases (181/201). • > than 100 cases have been recorded in hospitals, elderly care, worker dormitories, food processing plants (9 clusters), prisons, schools (8 clusters), shopping and ship settings. • Clusters of 50-100 cases: sports, bar, wedding, work, conference. • Household was the most common cluster venue and these were usually <10 people.
(Bouffanais & Lim, 2020)	Comment on super spreading hotspots for COVID-19.	- 95% of Singapore's cases have occurred in dormitories that house migrant workers (42,000 cases or 12.5% of the people living in the dormitories).
(Prakash, 2020) *preprint*	This synthesis is not conducted using standard systematic review methodology although a thorough search was conducted. They identified 20 situations that resulted in 418 infections across 32 instances from 44 individuals (8 had mild symptoms, 36 were asymptomatic).	- Situation (transmission rate): • Meals/ family events 15.7% to 66.7%. • Meetings (1 hour private meeting, 72.7% (43.6-98.0). • Open workspace with people movement (78.7% (CI. 70.3-85.3%)). • Singing (e.g., 2 hour practice 86.7% (CI.76.2- 93.2%), (Hamner et al., 2020)). • Prayer service (resulted in 1-7 secondary infections per infected individual). • Travelling in a car (closed environment) and talking had a high risk (100% (CI.20-100%)).

		• Public transportation, wearing a mask with no talking (~0%). • Hotels 53.3% (30.1-75.2%)/cruise ships 28.1% (27.3-29.0%) where space is shared for days . • Direct interaction with an infected sales agent 25.0% (10.2-49.5%). • Nightclub, attack rate among direct contacts >50%, among patrons of the nightclub 6.27% (5.15-7.61%) (Adam et al., 2020). • Restaurant overall attack rate (9.9% (CI: 5.3-17.7%) vs. those in the flow of the air conditioner 45.0% (25.8-65.8%). - Across all these super spreading events, number of infections caused depends on the number of close contacts and in most cases the index case was not detectable at the time of transmission.
(Y. Liu, Eggo, & Kucharski,)	This short communication summarizes 9 outbreaks resulting in 48 secondary infections among 137 people in late January.	- This makes for a secondary attack rate of 35% (95%: 27-44). • 3 outbreaks are meals in the home ARs (100%, 31%, 44%). • 1 restaurant meal (21%). • 4 unknown meals (100%, 87.5%, 11.7%, 21%). • 1 Chalet in France (45%).
Primary Research of Clusters		
(Walker et al., 2020)	Germany's first super spreading event.	- The Heinsberg outbreak associated with attending a carnival session on February 15, 2020. - Resulted in Germany's first large outbreak. More than 1,700 cases have been traced back to this event.
(Pfefferle et al., 2020)	This study uses viral genomics and variant calling to follow-up viral transmission during the initial outbreak in Hamburg Germany. They provide evidence of high viral dose transmission and low viral dose transmission.	- Patient 0 had contact with 132 people at his work place within the two days before developing symptoms. These transmission events are considered to be low dose transmission events. - One high risk contact co-worker and his spouse became positive for SARS-CoV-2. 1/33 high risk interactions and 0/98 low risk interactions were positive.

		- The spouse was asymptomatic, but virus was cultured from her oropharyngeal swab and both she and the index case viral load decreased quickly in the first 5 days of illness. - A familial cluster also demonstrates evidence of minority sequence variants, which is indicative of a high viral load exposure by droplets.
(Ghinai et al., 2020)	Chicago outbreaks associated with a family gathering and funeral.	- Index case had recently travelled and was mildly symptomatic at the time of transmission. Transmission events include sharing a meal and attending the funeral where there was a fair amount of contact (handshaking and hugging) - The birthday party was in a home with 9 family members (hugging, sharing food). - Church service transmission due to close conversation and sitting within one row for 90 minutes.
(A. James et al., 2020a)	Arkansas church outbreak in March 2020.	- Two pre-symptomatic people attended church gatherings and resulting attack rate was 35/92 and at least 26 additional cases in the community.
(Shen, Xu et al., 2020)	Jiaxing city outbreaks where gathering events included weddings, birthday parties and work.	- The secondary attack rate (SAR) was 0.6% (3/473). Cases that tested positive had contact with the index case; ate at the same table during the wedding, had close conversations, spent extended periods in the same room. The SAR among close contacts was 29% (2/7).
(Breton et al., 2020)	The first cluster of cases in France associated with a church week of prayer February 17-21, 2020, n=2000 Ro= 1.4 Serial interval = 4 days.	- The epidemic threshold was estimated as 4 cases per day. - The curve of incidence shows that the epidemic begun before a sanitary alert was given and that some of the attendees to the Christian week of prayer displayed symptoms before the event.
(Chaw et al., 2020; Wong, Jamaludin, Alikhan, & Chaw, 2020)	Cluster of cases in Malaysia related to Tablighi Jamaat's religious gathering. 19/75 attendees were infected at the event, they caused 52 secondary cases. - Negative binomial model was used to explore risk factors.	- The strongest attack rate (AR) was the gathering: (14.8% 95% CI: 7.1, 27.7]). - Household ARs of symptomatic cases were higher (14.4% 95% CI: 8.8, 19.9]) than asymptomatic or pre-symptomatic cases (5.4% 95% CI: 1.2, 9.6]).

		- Low ARs (< 1%) were observed for workplace and social settings.
(Chen et al., 2020)	A retrospective study of 141 COVID-19 cases in Chongquing January-February 2020. 90 were part of clusters and 51 were considered sporadic.	- 82% of clustered cases were associated with exposure at a family gathering.
(Adam et al., 2020) *preprint*	A notable cluster early in the epidemic in Hong Kong.	- 106 cases traced to bars and bands accounted for 30.4% of the local transmission in Hong Kong early in the epidemic. - This is thought to have been caused by a series of super spreading events among staff, bands, and patrons.
(Ye et al., 2020)	(in Chinese) An outbreak in Ningbo associated with a Buddhist rally in which the index case used shared transportation by bus.	- The overall attack rate was 37/1,283, 2.88% and infection rate 48/1,008, 4.76%. However, the bus attack rate 33.82% (23/68), and infection rate 38.24% (26/68) accounted for most of the transmission. - The presumed index case had started showing symptoms 1 day before participating in the event.
(Y. F. Liu et al., 2020 (in Chinese); Wu et al., 2020; Y. Zhang et al., 2020)	Cluster investigation in Tianjin up to February 22, 2020. N=115 cases in 33 clusters.	- 28 familial clusters. - 1 work place cluster (index case infected >6 people). - 3 transport clusters (2 airplanes, 1 train). - 1 department store cluster (1 infected sales associate infected 20 patrons and 3 co-workers).
(Correa-Martínez et al., 2020)	An outbreak associated with a ski resort town, Ishgl, Austria. Recognised by a local hospital, University Hospital Münster (UKM) in Germany. N-19 cases.	- 36/90 COVID cases had recently visited Ischgl (39.6%), a ski resort town. An apres-ski bar where a bar-keeper tested positive was also frequented by many of the positive cases. This bar is considered the potential source of the SSE.
(Park et al., 2020)	This report describes an outbreak of COVID-19 at a call center in Korea. Of 1,143 individuals tested for COVID, 97 (8.5%) were positive. The majority of these employees (94/97) were working on an 11th floor call center with 216 employees.	- The attack rate was 43.5% (95% CI: 36.9-50.4%). The household secondary attack rate among symptomatic cases was 16.2% (95% CI: 11.6-22%).
(Shen et al., 2020) *preprint*	The first outbreak investigation involved transportation to a worship event on buses. A second outbreak involving a 30-person workshop with shared transportation.	- Outbreak 1: Bus #2 had an attack rate of 34.3%, and no one on bus #1 was infected.

	Tracing from index case to secondary cases and relative time spent in proximity of index case are part of the investigation.	- In the second outbreak, the overall attack rate was 48.3%. - Fans and air conditioning units on recirculation mode are hypothesized to have helped circulate the virus within the room/bus. They suggest that airborne transmission must be partially responsible for the high attack rates.
(Qian et al., 2020) *preprint*	This study analyzed all outbreaks involving 3 or more cases reported to the municipal health commissions in China January 4-February 11, 2020. 318 indoor outbreaks are described across 120 cities. 80% of the outbreaks involved <5 people.	- 318 indoor outbreaks involving family (129), relatives (133), socially connected people (29) and socially disconnected people (24) are described across 120 cities. 80% of the outbreaks involved <5 people. 83 outbreaks had multiple venues so total >100% (n=318) - 79.9% occurred within a home, - 34.0% transportation, - 4.4% at restaurant, - 2.2% shopping venue and - 9.7% at other venues.

Methods:

A daily scan of the literature (published and pre-published) is conducted by the Emerging Science Group, PHAC. The scan has compiled COVID-19 literature since the beginning of the outbreak and is updated daily. Searches to retrieve relevant COVID-19 literature are conducted in Pubmed, Scopus, BioRxiv, MedRxiv, ArXiv, SSRN, Research Square and cross-referenced with the literature on the WHO COVID literature list, and COVID-19 information centers run by Lancet, BMJ, Elsevier and Wiley. The daily summary and full scan results are maintained in a Refworks database and an excel list that can be searched. Targeted keyword searching was conducted within these databases to identify relevant citations on COVID-19 and SARS-CoV-2. Search terms used included: social AND (network, gathering, cluster, outbreak), superspread* OR (super spread*). Approximately 278 citations were screened for relevance and additional outbreaks were drawn from the list of outbreak papers in previous reviews of super spreading events and workplace/indoor transmission events. This review contains research published up to August 18, 2020

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