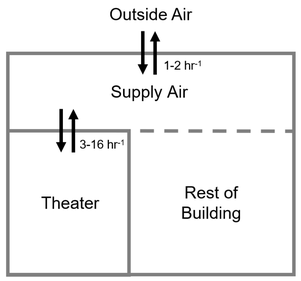
Measurement of Ventilation and Mixing Rates in Performance Halls to Characterize Risk of COVID-19 Transmission

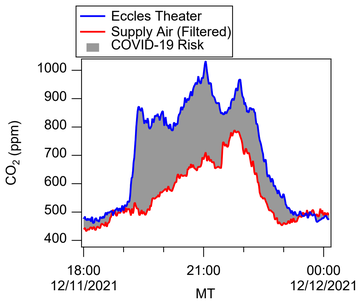
Sara Nielson and Demetrios Pagonis

Department of Chemistry and Biochemistry, Weber State University, Ogden, UT 84408

Measuring Ventilation to Assess Spread of Airborne Pathogens

- COVID-19 can be spread through airborne transmission
- Pathogen is emitted on the breath of infected individuals, and susceptible people then inhale this “second-hand air”
- Carbon dioxide (CO_2) exhaled by people is a good proxy for COVID-19 risk
- Because CO_2 is not removed by filters inside building air handlers, one must measure both the room and supply air CO_2 concentration

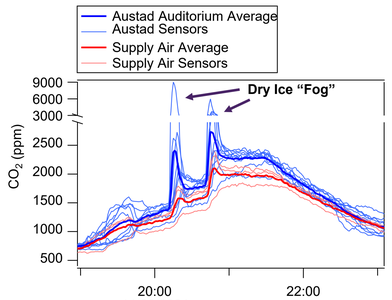


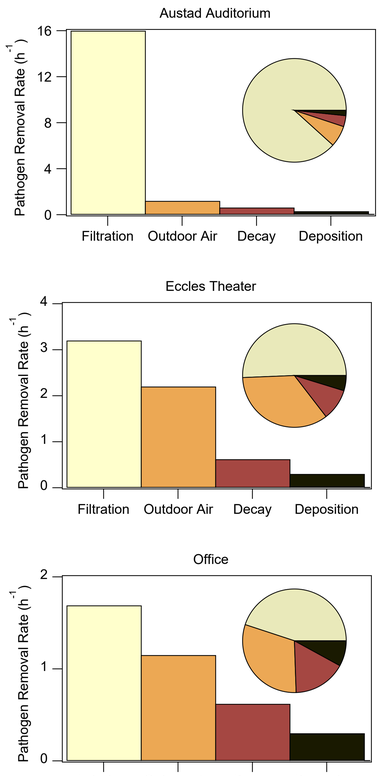


- Air circulates between theater and supply air and is filtered during each pass
- Outside air is also mixed into supply air during every pass. This exchange rate is variable

Majority of Mitigation Achieved Through Filtration in Air Handlers

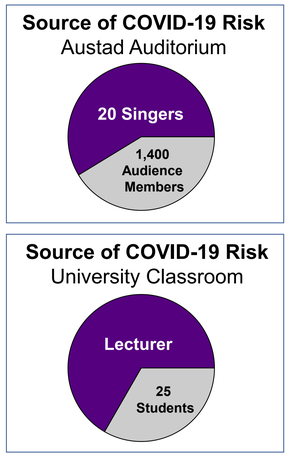
- In all performance venues, filtration of air by the air handler was the dominant removal pathway for pathogens
- WSU Facilities switched from MERV-8 to MERV-13 filters in 2020, giving high filter efficiency (>80%)
- Significant differences in recirculation rate was observed, with the larger theaters having very fast (16 h^{-1}) recirculation rates
- The Eccles Theater had recirculation rates similar to a typical classroom
- Because filtration dominates over ventilation with outdoor air, absolute CO_2 concentrations are not a reliable indicator of COVID risk in spaces with mechanical ventilation
- In rooms with mechanical ventilation, one should rely on the difference between room and supply air CO_2 concentration to assess risk of room-level pathogen transmission

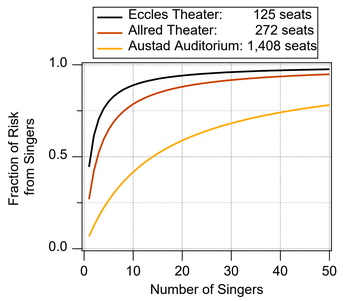




Performers are the Main Source of Risk

- Rate of pathogen emission by an infected person varies significantly based on their activity.
- Singing and speaking emit pathogen very efficiently compared to sitting quietly
- In performance halls, this means that singers and actors account for the majority of COVID-19 risk, even when outnumbered by audience members
- This makes performers a priority for any mitigation or testing efforts

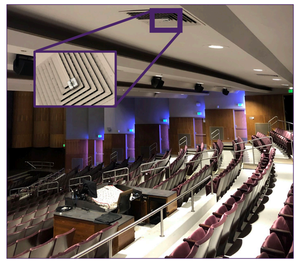




- In theaters with smaller audiences, performers can account for over 95% of COVID-19 risk
- This risk apportionment applies to any setting where one person is speaking and others are not, such as lectures

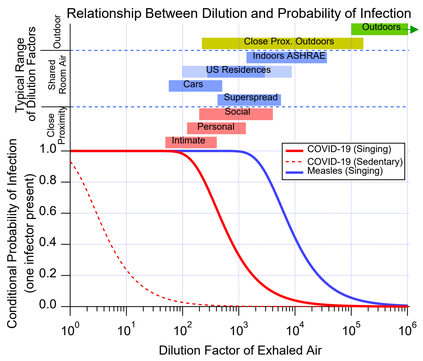
Sensor Deployment

- Twenty Aranet4 PRO non-dispersive infrared CO_2 sensors installed across Weber State University’s Val A. Browning Center
- Measured through the fall performance season: November & December 2021

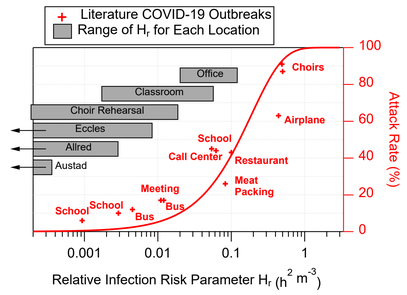


- Simultaneous measurement of in-room and supply air CO_2 concentrations allows for quantification of air recirculation and exchange rates
- Austad Auditorium (capacity: 1,408): thirteen sensors
- Allred Theater (capacity 272): five sensors
- Eccles Theater (capacity 125): two sensors
- Also measured an office, classroom, and choir room

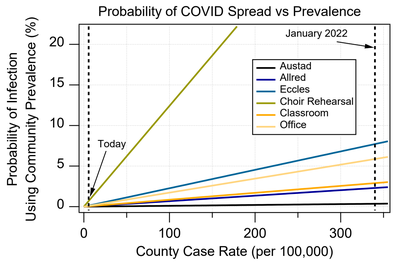
- All theaters are heavily reliant on the filters in their air handlers to actively remove particles (including emitted virus) from the air
- Because of the high recirculation rates, relative risk parameter (H_r) is sufficiently low to keep attack rates below 10%
- Browning Center is ensuring high quality filters (MERV-13) are installed in all air handlers
- Performances and rehearsals moved to spaces with best ventilation
- Audience locations moved for some performances to minimize unfiltered air exchange between performers and audience



Study Outcomes



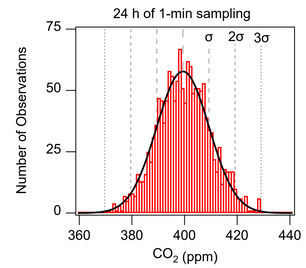
Location	$H_{r,\ Maximum}$	Attack Rate (Single Infector)
Austad	0.0003	0 – 0.2%
Allred	0.003	0 – 2%
Eccles	0.008	0 – 4%
Choir Rehearsal	0.018	0 – 10%
Classroom (lecturing)	0.06	0.9 – 26%
Office (talking)	0.12	10 – 48%

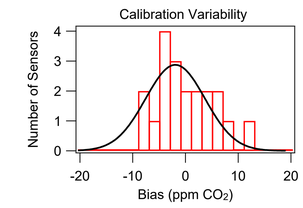


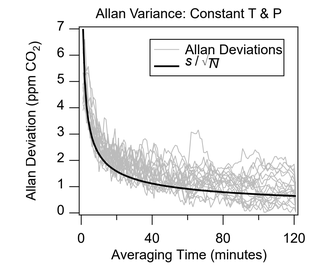
- Measurements made in this study allow for calculation of relative risk infection parameter H_r, which is related to attack rate of a pathogen in the figure at left
- H_r depends on the activity happening inside the room, event duration, room volume, and ventilation rate
- Ranges of attack rates expected for all venues measured are in the table at left. All spaces besides classroom and office assume a 20-person choir and a sell-out crowd. Classroom is a lecture with 25 students, and office is a 3-person meeting
- All calculations assume no masking
- Overall attack rate (bottom figure) is dependent on H_r, the number of people in the room, and the population incidence of the disease
- Bottom plot includes a 3-fold increase in infectivity to represent the omicron variant of COVID-19. All other plots use the infectivity of wild-type COVID-19

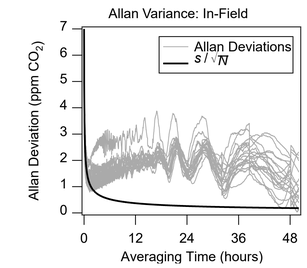
Aranet4 Sensor Statistics

- Aranet4 sensor variability is normally distributed with a standard deviation of 10 ppm CO_2
- Sensor-to-sensor variability is 5.4 ppm CO_2
- Typical CO_2 enhancements in occupied spaces are hundreds of ppm CO_2, and so these sensors are well-suited for indoor monitoring
- No significant sensor drift is observed on short timescales (under 2 h) at constant temperature and pressure
- Small day-to-day drifts of 3 ppm are observed
- Local minimum at 24 hours of averaging suggests that drift is due to changes in temperature and pressure









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