31 Lessons from COVID-19 & Necessary Actions for Future Pandemic Resilience for Safe Work, Safe School, & Safe Travel

Marissa V. Rainbolt[1], Emily Jones[1], Linsey C. Marr[2], David Michaels[3], Xiaodong Cao[4], Leslie R. Cadet[5], Shelly L. Miller[6], Lidia Morawska[7], Richard L. Corsi[8], Nira R. Pollock[9], Meira Levinson[10], Yuguo Li[11], Alasdair P S Munro[12], Kelly Grier[13], Qingyan Chen[14], John D. Macomber[15], Joseph G. Allen[1]

[1]Harvard T.H. Chan School of Public Health
[2]Civil and Environmental Engineering, Virginia Tech
[3]Milken Institute School of Public Health, George Washington University
[4]School of Aeronautic Science and Engineering, Beihang University
[5]Loma Linda University Health, Occupational Medicine Center
[6]Department of Mechanical Engineering, University of Colorado Boulder
[7]International Laboratory for Air Quality and Health (ILAQH), Queensland University
[8]College of Engineering, University of California, Davis
[9]Department of Laboratory Medicine, Boston Children's Hospital
[10]Harvard Graduate School of Education
[11]Department of Mechanical Engineering, The University of Hong Kong
[12]NIHR Southampton Clinical Research Facility and Biomedical Research Centre, University Hospital Southampton NHS Foundation Trust, Southampton, UK; Faculty of Medicine and Institute for Life Sciences, University of Southampton, Southampton, UK
[13]Ernst & Young Global Limited
[14]School of Mechanical Engineering, Purdue University
[15]Harvard Business School

Introduction

The COVID-19 pandemic activated scientists around the world from almost every discipline, generating advancements in our understanding of COVID-19 and respiratory infectious diseases more broadly at an unprecedented speed and scale. This scientific awakening created by the crisis has led to an explosion of knowledge. We have a duty to closely examine what we've learned, synthesize those learnings, and develop actionable recommendations that will better prepare the world to face the next major airborne infectious disease threat that will inevitably arrive, as well as seasonal respiratory infections such as influenza or the common cold.

Here, we identify 31 lessons learned during the COVID-19 pandemic and offer a set of recommendations for pandemic resilience in the domains of work, school, and travel. Each lesson in this report is underpinned by the critical need for action to reduce inequities in health, education, and economic opportunity that were exacerbated by the pandemic. They apply to the ongoing pandemic and future pandemics, but, just as importantly, they also should inform how we approach infectious disease risk mitigation in the places we work, learn, and move, every day. For far too long we have simply accepted high community rates of respiratory infection. We can do better. We have learned fundamental lessons that should lead to permanent changes in how we approach school, work, and travel going forward. And these lessons can also teach us something about how we protect ourselves from respiratory infectious diseases in other indoor spaces, e.g., homes, recreational facilities, and more.

Lessons on Infectious Disease Transmission & Scientific Alignment

Transmission of respiratory infectious diseases occurs mainly through the inhalation of viruses carried in microscopic respiratory particles known as "aerosols".

For the purposes of this report, respiratory particles that are small (100 μm in diameter or less) and suspended in the air are defined as aerosol particles, or simply, aerosols (Marr & Tang, 2021); aerosols can be carried on air currents over long distances, containing pathogens that can be directly inhaled, known as airborne transmission. This can occur in both the near-field (within the vicinity of the infection source) and far-field (greater distance away from the infection source). Respiratory particles that are large (greater than 100 μm in diameter) and fall quickly to the ground usually within two meters from the source are defined as large droplets; large droplets containing pathogens can land directly onto the mucous membranes of a susceptible person in the near-field, known as spray transmission. Transmission can also occur through touch, or indirect contact via a contaminated object known as a "fomite", where pathogens are transferred usually by hand to a susceptible person's mucous membranes (Marr & Tang, 2021).

Laboratory, field, modeling, and case studies have demonstrated that airborne transmission via inhalation of a virus-laden aerosols is important, if not dominant, for COVID-19. Viral ribonucleic acid (RNA) and infectious virus have been found in the exhaled air of infected individuals (Ma et al., 2020; Adenaiye et al., 2021). Infectious virus has been found in aerosols collected in hospital rooms (Lednicky et al., 2020; Santarpia et al., 2021). The virus has been shown to transmit through the air in animal models (Port et al., 2021; Kutter et al., 2020). Analyses of outbreaks during a choir rehearsal (Miller et al., 2020; Buonanno, Morawska, & Stabile, 2020), on a cruise ship (Azimi, Keshavarz, Cedeno Laurent, Stephens, & Allen, 2021), and in gyms (Lendacki, Teran, Gretsch, Fricchione, & Kerins, 2021; Groves et al.,2021), in a restaurant (Li et al., 2021), and on two buses (Ou et al., 2022) also demonstrated or implicated airborne transmission. A recent study involving a mechanistic model based on far field indoor exposures linked to quantitative microbial risk assessment (QMRA) was able to reasonably predict the number of infections in several outbreaks, underscoring the relative importance of inhalation dose (the number of particles inhaled and deposited in the respiratory system) of viruses embedded in aerosols in the far field (Parhizkar et al., 2021).

Aerosols can stay aloft for hours and travel beyond two meters.

Decades of research have shown that talking and coughing release far more aerosols than large droplets (Bourouiba, 2021), but this did not become widely recognized until demonstrated visually via laser light scattering (Anfinrud, Stadnytskyi, Bax, & Bax, 2020). We know from basic physics that such aerosols can remain suspended in the air for minutes to hours, during which they may be transported well over two meters by natural air currents (Wang et al., 2021). Aerosol travel distance is influenced by aerosol characteristics, such as size, and environmental characteristics, such as room airflow; even at a low room air velocity of 0.05 m/s, a 5 μm aerosol could travel over 20 meters before falling to the ground if emitted at a height of 1.5 meters (REHVA, 2021).

Risk of exposure to virus-laden aerosols increases in the near-field.

In the medical scientific community and in most publicly available health guidance throughout the COVID-19 pandemic, airborne transmission events are typically described as occurring when virus-laden aerosol are transported over long distances and inhaled by a susceptible person (Conly et al., 2020; Jones et al., 2020; Barber, 2020; US EPA, 2020). Conversely, spray transmission is typically described as occurring when large droplets that contain the virus land on the eyes, nose, or mouth of a susceptible person. This has been the primary explanation for infections that occur in the near-field to an infection source (Conly et al., 2020; WHO, 2020a).

The perception that exposures occurring in the near-field are entirely a result of the spray of large droplets contributes to an incomplete understanding of risk which exists across a spectrum of distances. In fact, aerosol is generally concentrated near the source and contributes to a greater risk of near-field exposure (US Centers for Disease Control and Prevention, 2021) than does the spray of large droplets (Chen, Zhang, Wei, Yen, & Li, 2020; Cortelessa et al., 2021). Thus, while transmission via the airborne route by virus-laden aerosol can occur in both the near- and far- fields, the near-field risk of transmission for a single individual within proximity to an infection source is generally greater than far-field risk (Chen, Zhang, Wei, Yen, & Li, 2020).

Erroneous thinking about airborne transmission has been traced to the misinterpretation of observations and experimental results from around 100 years ago.

Confusion was created based on a false dichotomy. Because spray transmission is considered to occur within two meters, it was assumed that airborne transmission occurs only in the far-field. This assumption rests on the observation that transmission occurs most commonly when people are in "close contact," but it mistakenly overlooks two critical facts: (1) people release significant quantities of aerosol along with large droplets and (2) aerosol is most concentrated close to the source, like cigarette smoke particles near a smoker (Chen, Zhang, Wei, Yen, & Li, 2020; Cortelessa et al., 2021). This, combined with a desire to refute miasma theory and to promote personal hygiene, contributed to the perpetuation of the idea that spray transmission was the dominant mode of spread of respiratory infectious disease (Randall, Ewing, Marr, Jimenez, & Bourouiba, 2021).

The legacy of the incorrect assumptions about airborne transmission persists in the form of continued misallocation of time, energy, and resources.

Early in the pandemic, health authorities concentrated almost exclusively on spray transmission and therefore emphasized one to two meters of distancing, extensive and frequent cleaning and disinfection of shared surfaces, and handwashing, while failing to recognize and promote the use of face coverings as an effective risk reduction measure. This approach allowed the virus to continue to spread, almost unabated, for months. This misstep demonstrates that it is critical to correctly identify dominant transmission pathways for a new disease as quickly as possible because these define the interventions that will most effectively slow the spread of disease. It is also critical not to dismiss any transmission pathways until the rationale for doing so is based on scientific evidence. A year later, after airborne transmission of COVID-19 was finally recognized by the WHO, the original messaging about large droplets remains stubbornly entrenched, and many resources continue to be devoted to excessive surface cleaning, or what some call "hygiene theater" despite its lack of effectiveness (Haug et al., 2020).

A new scientific record is being established that corrects historical mistakes on transmission routes.

An avalanche of publications has worked to overturn mistaken ideas about transmission routes for respiratory infectious diseases (Allen & Marr, 2020; Greenhalgh et al., 2021; Marr & Tang, 2021; Milton, 2020; Tang, Marr, & Milton, 2021; Morawska & Cao, 2020; Morawska & Milton, 2020; Tang, Marr, Li, & Dancer, 2021) and initiated a paradigm shift toward more accurate definitions (Marr & Tang, 2021). Medical training, including textbooks and course material, should similarly be updated with more descriptive and accurate definitions of transmission pathways. In addition, public health bodies and infection control clinicians should reassess which mitigation strategies should be recommended for different diseases and should develop prioritization schemes for mitigation strategies and precautions that could be used in future pandemics when there are mismatches between ideal mitigations and precautions and available resources.

A major shift in thinking, training, and practice around infection control is required.

Just as the historic dichotomy between spray transmission by large droplets in the near-field and airborne transmission by aerosol in the far-field has been shown to be incorrect (Randall, Ewing, Marr, Jimenez, & Bourouiba, 2021), the concept of high-risk medical aerosol generating procedures has been shown to be flawed. These procedures, in fact, do not produce significantly more respiratory aerosol than other activities (Klompas, Milton, Rhee, Baker, & Leekha, 2021) and infection control training and practice in hospitals should be updated to reflect this knowledge. Instead of allocating all N95 masks or isolation rooms for these procedures, all medical providers treating patients with respiratory viral infections, as well as other workers who may be exposed because they share the same air as the infected patients, should be equipped with adequate protections. Furthermore, hospitals should make contingency plans to increase negative pressure capacity quickly to mitigate the risks of housing infectious patients (Miller et al., 2017). These precautions should be taken in the event of any respiratory disease outbreak rather than exclusively during outbreaks of diseases traditionally thought to be transmitted via the airborne route (Klompas, Milton, Rhee, Baker, & Leekha, 2021).

Lessons on the Critical Role of Buildings & Establishing Effective Control Measures

Nearly all COVID-19 transmission has occurred indoors.

Transmission can occur anywhere, but the scientific record on COVID-19 has demonstrated that transmission occurs primarily indoors (Bulfone, Malekinejad, Rutherford, & Razani, 2021; Nishiura et al., 2020; Qian et al., 2020; Allen, VanRy et al., 2020). Aerosols can accumulate more quickly to higher concentrations indoors in spaces with low outdoor air ventilation and/or low levels of, or no, filtration. Outdoors, there is much greater dilution and dispersion of airborne particles, which significantly reduces concentrations of emitted aerosol in the near- and far-field.

The hierarchy of controls is an effective framework that can be applied to many hazards including the risk of infectious disease transmission.

The hierarchy of controls is the standard industrial hygiene approach to protecting workers that the United States Occupational Safety and Health Administration (OSHA) recommends employers follow when developing hazard control strategies. The hierarchy of controls is often depicted as an upside-down pyramid, with the most effective actions at the top followed by other actions in descending order of effectiveness. The most effective step is elimination of the hazard, followed by substitution, engineering controls, administrative controls, and personal protective equipment (PPE) (US Centers for Disease Control and Prevention, 2015). The specific application of the hierarchy of controls depends on the context. For example, early in the COVID-19 pandemic, the hierarchy of controls was used to suggest that staying home when possible (elimination) and only going out for essentials or only having critical workers come into the office (substitution) were effective controls (Deziel, Allen, Scheepers, & Levy, 2020; Allen & Macomber, 2020a; Sehgal & Milton, 2021).

Enhanced outdoor air ventilation is an effective tool for limiting disease transmission.

Existing ventilation standards were not designed to be effective against transmission of respiratory diseases (ASHRAE, 2019). One recommended mitigation strategy is to increase outdoor ventilation rates and/or improve filtration as one part of an overall strategy to reduce inhalation dose, which is a function of the concentration of virus in the air in addition to several other factors. Importantly, improved ventilation and filtration reduces both far-field transmission and near-field transmission (Li, Cheng, & Jia, 2021). Several enhanced ventilation rate targets for reducing transmission risk have been proposed by researchers - 30 cfm per person (14 l/s/p) (Allen & Macomber, 2020b), 21 cfm per person (10 l/s/p) (Li, Nazaroff, Bahnfleth, Wargocki, & Zhang, 2021; Li, Cheng, & Jia, 2021), and 4-6 equivalent air changes per hour (Allen and Ibrahim, 2021) - but no standard-setting body has put forth a firm target. It is imperative that the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), the United States Centers for Disease Control and Prevention (CDC), and the WHO develop ventilation targets for respiratory infectious diseases, including for non-healthcare settings.

Enhanced filtration in mechanically ventilated buildings is an effective strategy for reducing particle concentrations indoors.

In many buildings, a portion of the air is recirculated through a mechanical ventilation system, at which time it commonly passes through a filter. One widely used filter rating system is the Minimum Efficiency Reporting Value (MERV). Most buildings use at best a MERV 8 filter, which is a low-grade filter, and may capture as few as 20% of airborne particles 1.0 - 3.0 μm in size (ASHRAE, 2017). MERV 13 filters, which capture at least 85% of particles >1.0 μm in size (ASHRAE, 2017) are recommended as part of building system upgrades to minimize airborne disease transmission for buildings with mechanical systems that can handle the resistance of such a filter. It should be noted that no particle removal from filtration occurs when the mechanical system cycles off, such as periodically with demand control ventilation (DVC) systems. Therefore, DVC systems should be switched off or used with care during periods of heightened risk. Higher filtration efficiency is particularly important for buildings with within-room mechanical ventilation systems (e.g., unit ventilators). In large buildings with centralized rooftop units, the recommendation is still to install MERV 13 or higher filters, but the dilution that occurs through a large ducted system decreases the benefit of higher-grade filters. We recommend additional research on the performance and benefits of higher-grade filters in various building design configurations.

Portable air cleaners with HEPA filtration can be an effective risk mitigation strategy.

When sized correctly for the room, portable air cleaners with high efficiency particulate air (HEPA) filters are effective at reducing concentrations of particles indoors, including aerosol (Morawska et al., 2020). The efficacy depends on the filter performance, the fan speed, the size of the room, and the placement of the device. One useful metric that aids in the selection of an appropriate device is the Clean Air Delivery Rate (CADR), which combines filter performance with fan speed. We recommend developing additional metrics that also account for air mixing within the room, which can be used to better assess device performance.

Germicidal ultraviolet light is a proven technology for disinfecting building air.

When designed correctly, an upper room germicidal UV system consisting of lamps hung in the upper part of a room, or an in-duct system with lamps that radiate the air as it moves past the light, is very effective at inactivating airborne virus and bacteria (Xu et al 2003; Walker and Ko 2007; Reed 2010). The CDC has provided guidelines for the use of an upper-room system to control tuberculosis in health care facilities, which is applicable for COVID-19 mitigation (DHHS, 2009). Appropriate applications include indoor spaces with high occupant density, high-risk settings (e.g. healthcare), and little to no ability for adequate ventilation.

Masks work.

Basic physics demonstrates that masks can be effective at reducing the number of respiratory particles emitted into a space (Tang et al., 2021; Wood et al., 2018; Stockwell et al., 2018). The utility of face masks for reducing transmission of COVID-19 is supported by clinical and laboratory evidence (Howard et al., 2021) and a randomized controlled trial (Abaluck et al., 2021; Peeples, 2021). The two key determinants of how effective different masks can be are filtration capture efficiency and fit. Cloth masks are highly variable, ranging from less than 10% capture efficiency to up to nearly 100% for relevant particle sizes (Drewnick et al., 2021; Pan, Harb, Leng, & Marr, 2021). Surgical masks can be approximately 50-70% effective for source control (Brooks, et al., 2021; Pan, Harb, Leng, & Marr, 2021), and high-grade masks, like N95, FFP2, FFP3, KF94, KN95, can provide approximately 95% capture efficiency. With proper wearing of masks, the social distancing could be reduced to 0.5 m (Deng and Chen, 2022). If a mask is not properly worn, or is not flush to the skin, aerosol can escape without going through the filter material, greatly reducing the mask's overall effectiveness. An important aspect of masking, even if not fully fit, is that it can change the direction and speed of emissions in front of the person, impacting near-field transmission.

The use of rapid diagnostics can make work, school, and travel safer.

Rapid antigen tests are arguably better tools than traditional polymerase chain reaction (PCR) tests to determine whether individuals in the community are currently infectious with COVID-19 (Mina, Peto, García-Fiñana, Semple, & Buchan, 2021; Regev-Yochay et al., 2021). Due to their lower cost and faster turnaround time compared to PCR tests, rapid antigen tests are helpful tools for screening, contact testing, and for quickly identifying peak windows of infectiousness so transmission to others can be reduced. They also enable serial testing, a key strategy that involves frequent testing at different points in time, which can help reduce the risk of an outbreak at work or school (Larremore et al. 2021; Mina, Parker, & Larremore, 2020). For example, seven days of daily rapid antigen testing of individuals exposed to COVID-19 at school has been shown to be as effective as ten-day periods of isolation at controlling in-school COVID-19 transmission (Young et al. 2021). Rapid antigen tests are a powerful tool to help facilitate in-person work and schooling with minimal increased risk from COVID-19. Improved access to rapid antigen tests is a necessary control measure. Increased public education, faster deployment, decreased cost, increased access, and further consideration of reporting logistics (e.g., for at home use and for employee screening use) are necessary to facilitate broader use and optimal benefit.

The current system for collecting data on workplace exposures, interventions, and caseloads is inadequate to anticipate risks and make informed, data-driven decisions about school and workplace operations.

Globally, comprehensive, centralized collection of information about caseloads and interventions in schools and workplaces has been insufficient throughout the pandemic. In the US, the earliest and largest effort to collect and share these data for schools asked schools to volunteer information upon enrollment in the program and in a biweekly survey about current precautions against and impacts of COVID-19 (COVID-19 School Dashboard, 2021). A government-organized, centralized database that required participation from all schools would have provided a larger, less biased dataset which would have allowed public health experts to draw faster inferences about the effectiveness of interventions against COVID-19 in schools and would have supported efficient dissemination of guidance to schools regarding appropriate policies and operations. Gaps in tracking disease outbreaks in other potentially high-risk and essential workplaces such as food processing plants, grocery stores, and long-term care facilities also hampered efforts to adequately anticipate risks and make informed, data-driven decisions about workplace restrictions, resource allocations, and effective interventions. As a result, untargeted, one-size-fits-all lockdowns and reopens were utilized globally; these lockdowns may have been excessively costly to countless communities, students, and workers over the course of the pandemic.

Case cluster investigations routinely, and mistakenly, fail to evaluate building performance.

Despite the relevance of building system performance to disease transmission indoors, many cluster investigations routinely fail to collect data on the ventilation and filtration strategies in place at the time of transmission (Allen, Cadet, et al., 2021). When able to be collected, this information is invaluable for understanding what combination of environmental factors lead to the highest risk, and what control strategies may or may not be sufficient. In addition, epidemiological data from an outbreak or cluster can yield important information on key factors for modeling disease transmission (e.g., quanta generation rate, or the infectivity of the pathogen and infection source strength), but only if these building-level factors are included in the original investigation and reported. We recommend that all future cluster and disease outbreak investigations be paired with standardized building systems assessments.

Lessons on School Responses

School closures pose enormous, long-term, and unrecoverable costs to students.

In addition to education, schools provide nutritious food, access to counseling and mental health services, and opportunities for physical activity. When in-person schools are closed, it is more difficult (or impossible) for students to access these benefits and services. Globally, school closures due to the COVID-19 pandemic have been associated with learning loss (Agostinelli, Doepke, Sorrenti, & Zilibotti, 2020; Engzell, Frey, & Verhagen, 2021), negative mental health and social emotional outcomes (Larsen, Sand Helland, & Holt, 2020), and potential reduced lifetime earnings (Azevedo, Hasan, Goldemberg, Geven, & Iqbal, 2021).

School closures do not impact all communities and students equally.

For a multitude of reasons including personal and community vulnerability, historic and systemic racism in school systems, local COVID-19 transmission, and the politicization of school operation during the pandemic, minority and lower-income children are more likely both to have been negatively affected by school closures and to have familial preferences for remote schooling (Henderson, Peterson, & West, 2020; Levinson, Geller, Allen, & The Lancet COVID-19 Commission Task Force on Safe School Safe Work Safe Travel, 2021). Students in poorer countries around the world were also more likely to be affected by school closure during the COVID-19 pandemic (Buonsenso et al., 2021; UNESCO 2021; UNICEF 2021). These patterns of school closures may exacerbate existing inequities locally and globally for decades to come (Psacharopoulos, Collis, Patrinos, & Vegas, 2020).

The impacts of school closures are felt across the economy.

When parents are charged with supervising their child’s remote learning or when parents cannot count on schools consistently being open (perhaps due to hybrid schooling situations or due to quarantines after COVID-19 exposures), parents may not be able to perform their own work. During the COVID-19 pandemic, school closures were particularly challenging for families with two working parents, single parents, and parents who worked in essential industries outside the home. In the United States, widespread school closures occurred in March and 22 million jobs were lost between February and April 2020 (Handwerker, Meyer, Piacentini, Schultz, & Sveikauskas, 2020).

School closures disproportionately impact women in the workplace.

Impacts of school closures on working mothers of school-aged children were severe: the number of women in the workforce who were mothers dropped by 21.1% between March and

April 2020 in the United States, while the number of working fathers only dropped by 14.7% (US Census Bureau, 2021). Though this disparity in work status only lasted through October 2020, it is possible these school closures will permanently impact the earning potential of these women (US Census Bureau, 2021), representing a setback in the fight for gender equality in the workplace.

In-person schooling was deprioritized even as other non-essential or less essential community and economic activities continued.

In many countries during the COVID-19 pandemic, teaching was not considered essential work in the same way work at hospitals, grocery stores, and public utilities was. Mutual trust between citizens and government, teachers' unions and district staff, and parents and school officials was often absent during the COVID-19 pandemic. Fostering this trust is critical to keeping schools open (Levinson, Geller, Allen, & The Lancet COVID-19 Commission Task Force on Safe School Safe Work Safe Travel, 2021). With a higher prioritization of children's wellbeing and education, schools would have been among the last workplaces to close when levels of community viral transmission were excessive and among the first to reopen when community transmission dropped. Moreover, schools would have been provided with coordinated and standardized guidance from federal governments as well as the resources and support needed to foster trust and to mitigate the risks associated with in person learning. Unlike harms sustained by other sectors of the economy, the harms from loss of educational attainment or access to vital health and social functions provided by in-person schooling cannot be fully remediated through government financial support.

School infrastructure is not typically designed or managed for infection control.

Proper ventilation and in-school medical care (e.g. school nurses) are key to effective pandemic response. Schools are chronically under ventilated, with many United States schools failing to meet the minimum ASHRAE ventilation design standard (Corsi et al., 2021). Many schools also lack school nurses and hand washing supplies (Levinson et al, 2021). Even schools with school nurses have found it extremely difficult (or impossible) to manage the increased burden of clinical evaluation, data tracking, and potentially on-site testing required during the COVID-19 pandemic (Combe, 2020; Gormley et al., 2021). Additional school nursing resources should be deployed during any future pandemic.

It is possible to keep schools open without putting students and adults at excessive risk.

With proper mitigation measures in place, including ventilation and air cleaning enhancements (Corsi et al., 2021; Stabile et al., 2021) and masking, in-person schooling during the COVID-19 pandemic does not pose an elevated risk to students or teachers (Levinson et al., 2021; Lesser et al., 2021). In-person schooling has been associated with elevated household COVID-19 risk when relatively few COVID-19 mitigation measures were in place in schools; however, this association was not found among schools where seven or more COVID-19 mitigation measures were in place (Lessler et al., 2021). Similarly, extremely limited within-school COVID-19 transmission has been found in schools with control measures including masking, distancing, handwashing, and daily symptom screening (Zimmerman et al., 2021). While efforts should be made to reduce undue risk of infection to children, it should further be recognized that due to their low risk of severe COVID-19 (Smith, 2021), the harms of schools being closed for in-person learning outweigh the harms of infection.

Lessons on Workplace Responses

Essential workers, who are already disproportionately concentrated in more vulnerable minority and low-income communities, bore the brunt of the COVID-19 risk.

From the start of the pandemic, many white-collar workers (those whose work was computer- or telephone-based) were encouraged to work from home. In contrast, workers in industries categorized as “essential” – necessary to care for the sick or elderly, harvest crops or manufacture food products, deliver goods to stores or people’s homes, staff retail establishments or correctional institutions, or ensure public safety – were required to work in person. In the US, where approximately 40% of the workforce is employed in essential industries (D. Allen et al. 2020), Black and Brown workers, who are over-represented in high-risk essential industries (Gaffney, Himmelstein, & Woolhandler, 2021; Goldman, Pebley, Lee, Andrasfay, & Pratt, 2021) are also more likely to have lower incomes, live in crowded multigenerational households, and use public transportation to travel to work. These communities have been at greatest risk of serious illness and death from COVID-19 (J. T. Chen & Krieger, 2021; Feldman & Bassett, 2021). Inadequate efforts were made to prioritize the health and safety of these workers, first in requiring precautions in their workplaces, and later in distribution of vaccines when they became available.

Workplaces that were deemed essential were hotspots for COVID-19 transmission, but inadequate efforts were made to collect data on the number or severity of cases.

At the start of the pandemic, outbreaks were reported in hospitals and long-term care facilities, meat and poultry factories, correctional institutions, and other industries and worksites where virus exposure risk was high. Uncontrolled workplace exposures continued to occur throughout the pandemic. There is no system in place to collect data systematically on the number and severity of these cases, but it is clear that the number of workers sickened or killed as a result of workplace exposures is very large (Chen et al, 2021; Hawkins, Davis, Kriebel, 2020; Contreras et al, 2021) and workplace outbreaks have been an important driver of community spread as well (Taylor, Boulos, & Almond, 2020; Saitone, Aleks Schaefer, & Scheitrum, 2021).

Federal agencies with authority over the safety and health of workers have not required the systematic protections that might have prevented many of the illnesses and deaths that occurred following workplace exposures.

In the United States, OSHA has no standard to limit workplace exposures to airborne infectious agents. In the absence of a federal OSHA standard, several states issued their own rules that attempted to control workplace transmission of COVID-19 (Michaels & Wagner, 2020). Federal OSHA finally issued an Emergency Temporary Standard requiring employers in the healthcare industry to provide some protections against COVID-19 (US Occupational Safety and Health Administration, 2021) but the agency was not permitted to issue a similar rule that would have required public health precautions to be followed first in other essential industries and then in all workplaces after they reopened (Rolfsen, 2021).

Federal governments may need to help defray the costs of some risk reduction strategies.

To successfully keep potentially infectious workers from transmitting the virus in congregate employment settings, employers need rapid, accurate, low-cost testing programs, as well as access to a large quantity of inexpensive but effective respirators or other face coverings. Securing these tools will likely not be possible without action and perhaps the financial subsidy of federal governments. In addition, there is evidence that providing workers with paid sick leave prevents virus spread (Pichler, Wen, & Ziebarth, 2020); this also may require governmental subsidy, especially for smaller employers.

Lessons on Travel Responses

The risk of transmission of respiratory viruses among passengers while in flight is low.

Some studies report that transmission of COVID-19 can occur on airplanes (Chen et al., 2020a; Pavli et al., 2020; Speake et al., 2020; Khanh et al. 2020; Choi et al. 2020; Swadi et al. 2020). However, the global risk of disease transmission during air travel is estimated to be as low as 1 in 1.7 million (Pang et al., 2021). The low transmission risk on airplanes while in flight can be attributed to the environmental control systems onboard which, when running, deliver a 50:50 mix of outdoor air and recirculated air that passes through HEPA filters in most airplanes (National Academies of Sciences, Engineering, & Medicine, 2013). In addition, the air is delivered and returned within each row, which provides a high level of ventilation effectiveness.

Adequate gate-based ventilation should be maintained during airplane boarding and disembarkation.

When airplanes are parked at the gate, they rely on gate-based ventilation or auxiliary power units (APUs) to operate the ventilation system. In practice, ventilation is not always operated while airplanes are parked at the gate (Cao et al., 2018). When ventilation systems are not operating, filtered, clean air is not delivered and the risk of onboard disease transmission increases. This risk was documented in recommendations from the Airport Cooperative Research Program in 2013 (National Academies of Sciences, Engineering, & Medicine, 2013). To address these risks, airports or airlines should ensure gate-based ventilation systems are operational and should consider requiring masks during boarding and disembarkation.

Accessible, safe, and reliable public transit is essential for economic recovery and equity.

Public transit serves the vital functions of providing affordable transportation within urban areas, easing urban congestion and air pollution, and ultimately reducing passenger vehicle trips that contribute to emissions associated with climate change. Public transit systems were severely disrupted during the COVID-19 pandemic, with dramatic declines in both ridership and service (Hu & Chen, 2021; Deweese et al., 2020). There is relatively little scientific evidence indicating how transit vehicles like buses and trains may be conducive to viral transmission under normal operating conditions; additional research in this area is important to ensure that transit can operate as safely as possible, particularly to transport essential workers to and from their jobs during pandemic conditions. In the meantime, research from similar contexts suggests that the risk of COVID-19 transmission on public transit can be substantially reduced by controls including asking sick people to refrain from riding public transit, requiring or encouraging vaccination among riders, changing transit schedules to accommodate reduced crowding, improving ventilation or air cleaning. For example, buses can improve their ventilation substantially by opening as many windows, doors, or roof hatches as feasible (Edwards et al. 2021), deploying recirculating air cleaning systems using mechanical filtration or germicidal ultraviolet light, and requiring masks. Employers can support the implementation of these controls by requiring sick employees to stay home and by offering paid sick leave.

Conclusion

Every pandemic teaches us something, but if these lessons are not used to inform progress in the next crisis, history will inevitably repeat itself, with tragic results. Past learnings about transmission and effective risk reduction strategies that were gained through the study of other infectious diseases were translatable to COVID-19 and should have been applied early in this pandemic but were often summarily ignored. For example, the airborne nature of this threat, the power of ventilation and filtration to combat spread, the importance of masks, and the value of rapid diagnostic tests as a public health tool were all put forward in the first two months of this pandemic, but it took over a year for some of these strategies to be widely accepted and for broad action to be taken. New science generated during this pandemic reinforced prior knowledge and created new evidence-based solutions. It is incumbent on the scientific community and regulatory bodies to now incorporate this knowledge into standard practice, lest we find ourselves once again ignoring valuable acquired knowledge when the next pandemic hits. We do not need to start from scratch with each new crisis.

This report highlights 31 key lessons in the domains of work, school, and travel, but there are several fundamental themes that underpin these lessons. First is that airborne transmission, both in the near- and far-fields, is a critical, if not dominant, exposure pathway for SARS-CoV-2 and other respiratory viruses. Second is that touch transmission can happen but is rare for respiratory viruses and isn't likely to contribute to widespread transmission or superspreading events. Third is that nearly all transmission happens indoors. Establishing an understanding of exposure routes and identifying the highest risk environments for transmission should always be among the first critical steps in response to future disease threats, because this knowledge should determine effective control strategies.

These three fundamentals lead to a fourth key takeaway - how we design and operate our building ventilation and filtration systems matter. A paradigm shift in how we view and address the transmission of respiratory infectious diseases is underway (Morawska et al., 2021). Current bare minimum "acceptable" standards for ventilation and filtration are no longer acceptable and have contributed to the rapid spread of this virus, and others. It is time for standard-setting bodies such as ASHRAE to develop health-based standards for ventilation and filtration and building codes should adapt to align with these new priorities. Health-promoting building design and operation strategies can also double as climate adaptation techniques. For example, building occupants can be protected from health risks associated with climate change through enhanced building filtration to reduce indoor exposures to outdoor air pollution and wildfire smoke.

Fifth, engineering controls such as better ventilation and filtration should be considered in the context of the hierarchy of controls and with consideration of relative costs to implement each intervention. Establishing a hierarchy aids decision-makers in deciding which controls are needed when, and in what order they should be instituted and pulled back, when appropriate.

Sixth, the burdens of work and disease were not equally shared. This was a collective trauma that revealed the deep inequities in our societies across countries and within countries across wealth, class, status, and race/ethnicity. "Essential" workers performing critical services did not have the luxury of working from home, and therefore should have been equipped with hospital-grade respiratory protection and enhanced ventilation and filtration in their workplaces. To protect workers during the COVID-19 pandemic and from future disease risks, federal occupational health agencies should issue and enforce airborne infectious disease exposure standards, requiring every employer to develop a workplace infection control plan detailing the steps they will take to reduce or eliminate exposure risk. Enforceable standards like this are governments' most effective tools for protecting workers and ensuring that employers take steps to make workplaces safe. These steps should include requirements to ensure clean air (ventilation and filtration), expanded respiratory protection, and paid sick leave for workers who must quarantine or isolate, since there is evidence that paid leave decreases virus spread (Pichler, Wen, & Ziebarth, 2020).

Seventh, the cost of school closures - to students, women, and the economy - are devastating. The priority, even during a pandemic, should be for schools to remain open in person. This requires a reprioritization of support toward schools to enable the early implementation of stringent and scientifically supported control strategies in future pandemics.

Our ability to integrate these fundamental learnings into a more proactive and evidence-based framework for anticipating, recognizing, and controlling public health risks will have lasting impacts that influence the outcomes of future crises.

References

AASA, The School Superintendents Association, The National Association of Secondary School Principals, The National Association of Elementary School Principals, & Brown University Professor of Economics Emily Oster. (2021). COVID-19 School Response Dashboard. Retrieved November 19, 2021, from Qualtrics website: https://covidschooldashboard.com/

Abaluck, J., Kwong, L., Styczynski, A., Haque, A., Alamgir, K., Bates-Jefferys, E., & Zaman, N. (2021). *The Impact of Community Masking on COVID-19: A Cluster-Randomized Trial in Bangladesh* . Retrieved from https://www.poverty-action.org/publication/impact-community-masking-covid-19-cluster-randomized-trial-bangladesh

Adenaiye, O. O., Lai, J., Bueno de Mesquita, P. J., Hong, F., Youssefi, S., German, J., … Milton, D. K. (2021). Infectious Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) in Exhaled Aerosols and Efficacy of Masks During Early Mild Infection. *Clinical Infectious Diseases*. https://doi.org/10.1093/CID/CIAB797

Agostinelli, F., Doepke, M., Sorrenti, G., & Zilibotti, F. (2020). *When the Great Equalizer Shuts Down: Schools, Peers, and Parents in Pandemic Times*. Retrieved from http://www.nber.org/papers/w28264

Allen, D., Block, S., Cohen, J., Eckersley, P., Eifler, M., & Weyl, E. G. (2020). *Roadmap to Pandemic Resilience: Massive Scale Testing, Tracing, and Supported Isolation (TTSI) as the Path to Pandemic Resilience for a Free Society*. Retrieved from https://ethics.harvard.edu/files/center-for-ethics/files/roadmaptopandemicresilience_updated_4.20.20_0.pdf

Allen, J. G., Cadet, L. R., Cao, X., Chen, Q., Corsi, R., Jones, E. R., … Miller, S. L. (2021). Building-related risk factors are a critical, but missing, component of SARS-CoV-2 outbreak investigations. *The Lancet COVID-19 Commission*. Retrieved from www.covid19commission.org.

Allen, J. G., & Ibrahim, A. M. (2021). Indoor Air Changes and Potential Implications for SARS-CoV-2 Transmission. *JAMA*. https://doi.org/10.1001/jama.2021.5053

Allen, J. G., & Macomber, J. D. (2020a). Healthy Buildings: How Indoor Spaces Drive Performance and Productivity. *Harvard University Press*. https://doi.org/10.4159/9780674246102

Allen, J. G., & Macomber, J. D. (2020b, April). What makes an office building "healthy?" *Harvard Business Review*. Retrieved from https://hbr.org/2020/04/what-makes-an-office-building-

healthy
Allen, J. G., & Marr, L. C. (2020). Recognizing and controlling airborne transmission of SARS-CoV-2 in indoor environments. *Indoor Air*, *30*(4). Retrieved from https://onlinelibrary.wiley.com/doi/full/10.1111/ina.12697#.Xuy9Al_2Jvw.twitter
Allen, J. G., VanRy, M., Jones, E. R., Sommers, B. D., Levinson, M., Cao, X., … Sciences, M. (2021). *The Lancet COVID-19 Commission: Six Priority Areas*. Retrieved from https://covid19commission.org/safe-work-travel
Anfinrud, P., Stadnytskyi, V., Bax, C. E., & Bax, A. (2020). Visualizing Speech-Generated Oral Fluid Droplets with Laser Light Scattering. *New England Journal of Medicine*, *382*(21), 2061–2063. https://doi.org/10.1056/NEJMC2007800/SUPPL_FILE/NEJMC2007800_DISCLOSURES.PDF
ASHRAE. (2017). Standard 52.2-2017 -- Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size . Retrieved November 19, 2021, from ASHRAE website: https://www.techstreet.com/standards/ashrae-52-2-2017?product_id=1942059
ASHRAE. (2019). Standard 62.1-2019 -- Ventilation for Acceptable Indoor Air Quality. Retrieved November 19, 2021, from ASHRAE website: https://www.techstreet.com/ashrae/standards/ashrae-62-1-2019?product_id=2088533
Azevedo, J. P., Hasan, A., Goldemberg, D., Geven, K., & Iqbal, S. A. (2021). Simulating the Potential Impacts of COVID-19 School Closures on Schooling and Learning Outcomes: A Set of Global Estimates. *The World Bank Research Observer*, *36*(1), 1–40. https://doi.org/10.1093/WBRO/LKAB003
Azimi, P., Keshavarz, Z., Cedeno Laurent, J. G., Stephens, B., & Allen, J. G. (2021). Mechanistic transmission modeling of COVID-19 on the Diamond Princess cruise ship demonstrates the importance of aerosol transmission. *Proceedings of the National Academy of Sciences*, *118*(8), e2015482118. https://doi.org/10.1073/pnas.2015482118
Barber, C. (2020, October 1). Protecting against COVID's Aerosol Threat. Retrieved November 19, 2021, from Scientific American website: https://www.scientificamerican.com/article/protecting-against-covids-aerosol-threat/
Bourouiba, L. (2021). The Fluid Dynamics of Disease Transmission. *Annual Review of Fluid Mechanics*, *53*, 473–508. https://doi.org/10.1146/ANNUREV-FLUID-060220-113712
Brooks, J. T., Beezhold, D. H., Noti, J. D., Coyle, J. P., Derk, R. C., Blachere, F. M., & Lindsley, W. G. (2021). Maximizing Fit for Cloth and Medical Procedure Masks to Improve Performance and Reduce SARS-CoV-2 Transmission and Exposure, 2021. *MMWR. Morbidity and Mortality Weekly Report*, *70*(7), 1–4. https://doi.org/10.15585/mmwr.mm7007e1
Bulfone, T. C., Malekinejad, M., Rutherford, G. W., & Razani, N. (2021). Outdoor Transmission of SARS-CoV-2 and Other Respiratory Viruses: A Systematic Review. *The Journal of Infectious Diseases*, *223*(4), 550–561. https://doi.org/10.1093/INFDIS/JIAA742
Buonanno, G., Morawska, L., & Stabile, L. (2020). Quantitative assessment of the risk of airborne transmission of SARS-CoV-2 infection: Prospective and retrospective applications. *Environment International*, *145*, 106112. https://doi.org/10.1016/J.ENVINT.2020.106112
Buonsenso, D., Roland, D., De Rose, C., Vásquez-Hoyos, P., Ramly, B., Chakakala-Chaziya, J. N., … González-Dambrauskas, S. (2021). Schools closures during the COVID-19 pandemic. *Pediatric Infectious Disease Journal*, *40*(4), E146–E150.

https://doi.org/10.1097/INF.0000000000003052
Cao, X., Zevitas, C. D., Spengler, J. D., Coull, B., McNeely, E., Jones, B., … Allen, J. G. (2018). The on-board carbon dioxide concentrations and ventilation performance in passenger cabins of US domestic flights. *Indoor and Built Environment*, *28*(6), 761–771. https://doi.org/10.1177/1420326X18793997
Chen, J., He, H., Cheng, W., Liu, Y., Sun, Z., Chai, C., … Chen, Z. (2020). Potential transmission of SARS-CoV-2 on a flight from Singapore to Hangzhou, China: An epidemiological investigation. *Travel Medicine and Infectious Disease*, *36*, 101816. https://doi.org/10.1016/J.TMAID.2020.101816
Chen, J. T., & Krieger, N. (2021). Revealing the Unequal Burden of COVID-19 by Income, Race/Ethnicity, and Household Crowding: US County Versus Zip Code Analyses. *Journal of Public Health Management and Practice*, *27*, S46–S56. https://doi.org/10.1097/PHH.0000000000001263
Chen, W., Zhang, N., Wei, J., Yen, H. L., & Li, Y. (2020). Short-range airborne route dominates exposure of respiratory infection during close contact. *Building and Environment*, *176*, 106859. https://doi.org/10.1016/J.BUILDENV.2020.106859
Chen, Y.-H., Glymour, M., Riley, A., Balmes, J., Duchowny, K., Harrison, R., … Bibbins-Domingo, K. (2021). Excess mortality associated with the COVID-19 pandemic among Californians 18–65 years of age, by occupational sector and occupation: March through October 2020. *MedRxiv*, 2021.01.21.21250266. https://doi.org/10.1101/2021.01.21.21250266
Choi, E. M., Chu, D. K. W., Cheng, P. K. C., Tsang, D. N. C., Peiris, M., Bausch, D. G., … Watson-Jones, D. (2020). In-Flight Transmission of SARS-CoV-2 . *Emerging Infectious Diseases*, *26*(11), 2713–2716. https://doi.org/10.3201/EID2611.203254
Combe, L. G. (2020). Reopening Schools During COVID-19: School Nurse Ethical Conflicts and Moral Dilemmas. *NASN School Nurse*, *35*(6), 308–312. https://doi.org/10.1177/1942602X20963522
Conly, J., Seto, W. H., Pittet, D., Holmes, A., Chu, M., & Hunter, P. R. (2020). Use of medical face masks versus particulate respirators as a component of personal protective equipment for health care workers in the context of the COVID-19 pandemic. *Antimicrobial Resistance and Infection Control*, *9*(1), 1–7. https://doi.org/10.1186/S13756-020-00779-6/METRICS
Contreras, Z., Ngo, V., Pulido, M., Washburn, F., Meschyan, G., Gluck, F., … Halai, U. A. (2021). Industry Sectors Highly Affected by Worksite Outbreaks of Coronavirus Disease, Los Angeles County, California, USA, March 19-September 30, 2020. *Emerging Infectious Diseases*, *27*(7), 1769–1775. https://doi.org/10.3201/EID2707.210425
Corsi, R., Miller, S. L., VanRy, M. G., Marr, L. C., Cadet, L. R., Pollock, N. R., … Allen, J. G. (2021). *Designing infectious disease resilience into school buildings through improvements to ventilation and air cleaning*. Retrieved from https://covid19commission.org/safe-work-travel
Cortellessa, G., Stabile, L., Arpino, F., Faleiros, D. E., van den Bos, W., Morawska, L., & Buonanno, G. (2021). Close proximity risk assessment for SARS-CoV-2 infection. *Science of The Total Environment*, *794*, 148749. https://doi.org/10.1016/J.SCITOTENV.2021.148749
Deng, Z., & Chen, Q. (2021). What is suitable social distancing for people wearing face masks during the COVID-19 pandemic? *Indoor Air*. https://doi.org/10.1111/INA.12935
Department of Health and Human Services. (2009). Environmental control for tuberculosis:

basic upper-room ultraviolet germicidal irradiation guidelines for healthcare settings. In *CDC*. https://doi.org/10.26616/NIOSHPUB2009105
Deweese, J., Hawa, L., Demyk, H., Davey, Z., Belikow, A., & El-geneidy, A. (2020). A Tale of 40 Cities: A Preliminary Analysis of Equity Impacts of COVID-19 Service Adjustments across North America. *Transport Findings*.
Deziel, N. C., Allen, J. G., Scheepers, P. T. J., & Levy, J. I. (2020). The COVID-19 pandemic: a moment for exposure science. *Journal of Exposure Science & Environmental Epidemiology 2020 30:4*, *30*(4), 591–593. https://doi.org/10.1038/s41370-020-0225-3
Drewnick, F., Pikmann, J., Fachinger, F., Moormann, L., Sprang, F., & Borrmann, S. (2021). Aerosol filtration efficiency of household materials for homemade face masks: Influence of material properties, particle size, particle electrical charge, face velocity, and leaks. *Aerosol Science and Technology*, *55*(1), 63–79. https://doi.org/10.1080/02786826.2020.1817846/SUPPL_FILE/UAST_A_1817846_SM6292.DOCX
Edwards, N. J., Widrick, R., Wilmes, J., Breisch, B., Gerschefske, M., Sullivan, J., … Espinoza-Calvio, A. (2021). Reducing COVID-19 Airborne Transmission Risks on Public Transportation Buses: An Empirical Study on Aerosol Dispersion and Control. *MedRxiv*, 2021.02.25.21252220. https://doi.org/10.1101/2021.02.25.21252220
Engzell, P., Frey, A., & Verhagen, M. (2021). Learning loss due to school closures during the COVID-19 pandemic. *PNAS*, *118*. https://doi.org/10.1073/pnas.2022376118/-/DCSupplemental.y
Feldman, J. M., & Bassett, M. T. (2021). Variation in COVID-19 Mortality in the US by Race and Ethnicity and Educational Attainment. *JAMA Network Open*, *4*(11), e2135967–e2135967. https://doi.org/10.1001/JAMANETWORKOPEN.2021.35967
Gaffney, A. W., Himmelstein, D. U., & Woolhandler, S. (2021). Trends and Disparities in Teleworking During the COVID-19 Pandemic in the USA: May 2020–February 2021. *Journal of General Internal Medicine*, 1. https://doi.org/10.1007/S11606-021-07078-9
Goldman, N., Pebley, A. R., Lee, K., Andrasfay, T., & Pratt, B. (2021). Racial and ethnic differentials in COVID-19-related job exposures by occupational standing in the US. *PLoS ONE*, *16*(9). https://doi.org/10.1371/JOURNAL.PONE.0256085
Gormley, J. M., Poirier, V., Hassey, K. A., Van Pelt, M., & Ye, L. (2021). School Nurses' Reports on Reopening Roles, Practices, and Concerns During the COVID-19 Pandemic at the Start of the 2020–2021 School Year: *The Journal of School Nursing*. https://doi.org/10.1177/10598405211054805
Greenhalgh, T., Jimenez, J. L., Prather, K. A., Tufekci, Z., Fisman, D., & Schooley, R. (2021). Ten scientific reasons in support of airborne transmission of SARS-CoV-2. *The Lancet*, *397*(10285), 1603–1605. https://doi.org/10.1016/S0140-6736(21)00869-2
Groves, L. M., Usagawa, L., Elm, J., Low, E., Manuzak, A., Quint, J., … Kemble, S. K. (2021). Community Transmission of SARS-CoV-2 at Three Fitness Facilities — Hawaii, June–July 2020. *MMWR*, *70*(9), 316–320. https://doi.org/10.15585/MMWR.MM7009E1
Handwerker, E. W., Meyer, P. B., Piacentini, J., Schultz, M., & Sveikauskas, L. (2020). Employment recovery in the wake of the COVID-19 pandemic. *Monthly Labor Review*, *2020*, 1–24. https://doi.org/10.21916/MLR.2020.27
Haug, N., Geyrhofer, L., Londei, A., Dervic, E., Desvars-Larrive, A., Loreto, V., … Klimek, P. (2020).

Ranking the effectiveness of worldwide COVID-19 government interventions. *Nature Human Behaviour* , *4*(12), 1303–1312. https://doi.org/10.1038/s41562-020-01009-0
Hawkins, D., Davis, L., & Kriebel, D. (2021). COVID-19 deaths by occupation, Massachusetts, March 1-July 31, 2020. *American Journal of Industrial Medicine*, *64*(4), 238–244. https://doi.org/10.1002/AJIM.23227
Henderson, M., Peterson, P., & West, M. (2020). Pandemic Parent Survey Finds Perverse Pattern: Students Are More Likely to Be Attending School in Person Where Covid Is Spreading More Rapidly . *Education Next*. Retrieved from https://www.educationnext.org/pandemic-parent-survey-finds-perverse-pattern-students-more-likely-to-be-attending-school-in-person-where-covid-is-spreading-more-rapidly/
Howard, J., Huang, A., Li, Z., Tufekci, Z., Zdimal, V., van der Westhuizen, H. M., … Rimoin, A. W. (2021). An evidence review of face masks against COVID-19. *Proceedings of the National Academy of Sciences*, *118*(4). https://doi.org/10.1073/PNAS.2014564118
Hu, S., & Chen, P. (2021). Who left riding transit? Examining socioeconomic disparities in the impact of COVID-19 on ridership. *World Transit Research*, *90*. https://doi.org/10.1016/J.TRD.2020.102654
Jones, N. R., Qureshi, Z. U., Temple, R. J., Larwood, J. P. J., Greenhalgh, T., & Bourouiba, L. (2020). Two metres or one: what is the evidence for physical distancing in covid-19? *BMJ*, *370*, m3223. https://doi.org/10.1136/BMJ.M3223
Khanh, N. C., Thai, P. Q., Quach, H. L., Thi, N. A. H., Dinh, P. C., Duong, T. N., … Anh, D. D. (2020). Transmission of SARS-CoV 2 During Long-Haul Flight . *Emerging Infectious Diseases*, *26*(11), 2617–2624. https://doi.org/10.3201/EID2611.203299
Klompas, M., Milton, D. K., Rhee, C., Baker, M. A., & Leekha, S. (2021). Current Insights Into Respiratory Virus Transmission and Potential Implications for Infection Control Programs. *Annals of Internal Medicine*. https://doi.org/10.7326/M21-2780
Kutter, J. S., de Meulder, D., Bestebroer, T. M., Lexmond, P., Mulders, A., Richard, M., … Herfst, S. (2021). SARS-CoV and SARS-CoV-2 are transmitted through the air between ferrets over more than one meter distance. *Nature Communications*, *12*(1), 1–8. https://doi.org/10.1038/s41467-021-21918-6
Larremore, D. B., Wilder, B., Lester, E., Shehata, S., Burke, J. M., Hay, J. A., … Parker, R. (2021). Test sensitivity is secondary to frequency and turnaround time for COVID-19 screening. *Science Advances*, *7*(1). https://doi.org/10.1126/SCIADV.ABD5393/SUPPL_FILE/PAPV2.PDF
Larsen, L., Sand Helland, M., & Holt, · Tonje. (2020). The impact of school closure and social isolation on children in vulnerable families during COVID-19: a focus on children’s reactions. *European Child & Adolescent Psychiatry*, *1*, 3. https://doi.org/10.1007/s00787-021-01758-x
Lednicky, J. A., Lauzardo, M., Fan, Z. H., Jutla, A. S., Tilly, T. B., Gangwar, M., … Wu, C.-Y. (2020). Viable SARS-CoV-2 in the air of a hospital room with COVID-19 patients. *MedRxiv*, 2020.08.03.20167395. https://doi.org/10.1101/2020.08.03.20167395
Lendacki, F. R., Teran, R. A., Gretsch, S., Fricchione, M. J., & Kerins, J. L. (2021). COVID-19 Outbreak Among Attendees of an Exercise Facility — Chicago, Illinois, August–September 2020. *MMWR*, *70*(9), 321–325. https://doi.org/10.15585/MMWR.MM7009E2
Lessler, J., Grabowski, M. K., Grantz, K. H., Badillo-Goicoechea, E., Metcalf, C. J. E., Lupton-

Smith, C., … Stuart, E. A. (2021). Household COVID-19 risk and in-person schooling. *Science*, *372*(6546), 1092–1097. https://doi.org/10.1126/SCIENCE.ABH2939

Levinson, M., Geller, A. C., Allen, J. G., & The Lancet COVID-19 Commission Task Force on SafeSchool Safe Work Safe Travel. (2021). Health Equity, Schooling Hesitancy, and the Social Determinants of Learning. *The Lancet Regional Health - Americas*, *2*, 100032. https://doi.org/10.1016/J.LANA.2021.100032

Li, Y., Cheng, P., & Jia, W. (2021). Poor ventilation worsens short-range airborne transmission of respiratory infection. *Indoor Air*. https://doi.org/10.1111/INA.12946

Li, Y., Nazaroff, W. W., Bahnfleth, W., Wargocki, P., & Zhang, Y. (2021). The COVID-19 pandemic is a global indoor air crisis that should lead to change: A message commemorating 30 years of Indoor Air. *Indoor Air*, *31*(6), 1683–1686. https://doi.org/10.1111/INA.12928

Li, Y., Qian, H., Hang, J., Chen, X., Cheng, P., Ling, H., … Kang, M. (2021). Probable airborne transmission of SARS-CoV-2 in a poorly ventilated restaurant. *Building and Environment*, *196*, 107788. https://doi.org/10.1016/j.buildenv.2021.107788

Ma, J., Qi, X., Chen, H., Li, X., Zhang, Z., Wang, H., … Yao, M. (2020). COVID-19 patients in earlier stages exhaled millions of SARS-CoV-2 per hour. *Clinical Infectious Diseases*, *72*(10), e652–e654. https://doi.org/10.1093/CID/CIAA1283

Marr, L. C., & Tang, J. W. (2021). A Paradigm Shift to Align Transmission Routes With Mechanisms. *Clinical Infectious Diseases*, *73*(10), 1747–1749. https://doi.org/10.1093/CID/CIAB722

Michaels, D., & Wagner, G. R. (2020). Occupational Safety and Health Administration (OSHA) and Worker Safety During the COVID-19 Pandemic. *JAMA*, *324*(14), 1389–1390. https://doi.org/10.1001/JAMA.2020.16343

Miller, S. L., Clements, N., Elliott, S. A., Subhash, S. S., Eagan, A., & Radonovich, L. J. (2017). Implementing a negative-pressure isolation ward for a surge in airborne infectious patients. *American Journal of Infection Control*, *45*(6), 652. https://doi.org/10.1016/J.AJIC.2017.01.029

Miller, S. L., Nazaroff, W. W., Jimenez, J. L., Boerstra, A., Buonanno, G., Dancer, S. J., … Noakes, C. (2020). Transmission of SARS-CoV-2 by inhalation of respiratory aerosol in the Skagit Valley Chorale superspreading event. *Indoor Air*, ina.12751. https://doi.org/10.1111/ina.12751

Milton, D. K. (2020). A Rosetta Stone for Understanding Infectious Drops and Aerosols. *Journal of the Pediatric Infectious Diseases Society*, *9*(4), 413–415. https://doi.org/10.1093/JPIDS/PIAA079

Mina, M. J., Parker, R., & Larremore, D. B. (2020). Rethinking Covid-19 Test Sensitivity — A Strategy for Containment. *New England Journal of Medicine*, *383*(22), e120. https://doi.org/10.1056/NEJMP2025631/SUPPL_FILE/NEJMP2025631_DISCLOSURES.PDF

Mina, M. J., Peto, T. E., García-Fiñana, M., Semple, M. G., & Buchan, I. E. (2021). Clarifying the evidence on SARS-CoV-2 antigen rapid tests in public health responses to COVID-19. *The Lancet*, *397*(10283), 1425–1427. https://doi.org/10.1016/S0140-6736(21)00425-6

Morawska, L, Allen, J., Bahnfleth, W., Bluyssen, P., Boerstra, A., Buonanno, G., … M, Y. (2021). A paradigm shift to combat indoor respiratory infection. *Science*, *372*(6543), 689–691. https://doi.org/10.1126/SCIENCE.ABG2025

Morawska, Lidia, & Cao, J. (2020). Airborne transmission of SARS-CoV-2: The world should face the reality. *Environment International*, *139*, 105730. https://doi.org/10.1016/J.ENVINT.2020.105730

Morawska, Lidia, & Milton, D. K. (2020). It is Time to Address Airborne Transmission of COVID-19. *Clinical Infectious Diseases : An Official Publication of the Infectious Diseases Society of America*. https://doi.org/10.1093/cid/ciaa939

Morawska, Lidia, Tang, J. W., Bahnfleth, W., Bluyssen, P. M., Boerstra, A., Buonanno, G., … Yao, M. (2020). How can airborne transmission of COVID-19 indoors be minimised? *Environment International*, *142*, 105832. https://doi.org/10.1016/J.ENVINT.2020.105832

National Academies of Sciences, E. and M. (2013). Infectious Disease Mitigation in Airports and on Aircraft. *The National Academies of Sciences* . https://doi.org/10.17226/22512

Nishiura, H., Oshitani, H., Kobayashi, T., Saito, T., Sunagawa, T., Matsui, T., … Suzuki, M. (2020). Closed environments facilitate secondary transmission of coronavirus disease 2019 (COVID-19). *MedRxiv*, 2020.02.28.20029272. https://doi.org/10.1101/2020.02.28.20029272

Ou, C., Hu, S., Luo, K., Yang, H., Hang, J., Cheng, P., … Li, Y. (2022). Insufficient ventilation led to a probable long-range airborne transmission of SARS-CoV-2 on two buses. *Building and Environment*, *207*, 108414. https://doi.org/10.1016/J.BUILDENV.2021.108414

Pan, J., Harb, C., Leng, W., & Marr, L. C. (2020). Inward and outward effectiveness of cloth masks, a surgical mask, and a face shield. *MedRxiv*. https://doi.org/10.1101/2020.11.18.20233353

Pang, J. K., Jones, S. P., Waite, L. L., Olson, N. A., Armstrong, J. W., Atmur, R. J., & Cummins, J. J. (2021). Probability and estimated risk of SARS-CoV-2 transmission in the air travel system. *Travel Medicine and Infectious Disease*, *43*. https://doi.org/10.1016/J.TMAID.2021.102133

Pavli, A., Smeti, P., Hadjianastasiou, S., Theodoridou, K., Spilioti, A., Papadima, K., … Maltezou, H. C. (2020). In-flight transmission of COVID-19 on flights to Greece: An epidemiological analysis. *Travel Medicine and Infectious Disease*, *38*, 101882. https://doi.org/10.1016/J.TMAID.2020.101882

Pichler, S., Wen, K., & Ziebarth, N. R. (2020). COVID-19 emergency sick leave has helped flatten the curve in the United States. *Health Affairs*, *39*(12), 2197–2204. https://doi.org/10.1377/HLTHAFF.2020.00863/ASSET/IMAGES/LARGE/FIGUREEX4.JPEG

Port, J. R., Yinda, C. K., Avanzato, V. A., Schulz, J. E., Holbrook, M. G., Doremalen, N. van, … Munster, V. J. (2021). Increased aerosol transmission for B.1.1.7 (alpha variant) over lineage A variant of SARS-CoV-2. *BioRxiv*, 2021.07.26.453518. https://doi.org/10.1101/2021.07.26.453518

Psacharopoulos, G., Collis, V., Patrinos, H. A., & Vegas, E. (2020). Lost Wages: The COVID-19 Cost of School Closures. *SSRN Electronic Journal*. https://doi.org/10.2139/SSRN.3682160

Qian, H., Miao, T., Liu, L., Zheng, X., Luo, D., & Li, Y. (2020). Indoor transmission of SARS-CoV-2. *Indoor Air*, 2020.04.04.20053058. https://doi.org/10.1101/2020.04.04.20053058

Randall, K., Ewing, E. T., Marr, L. C., Jimenez, J. L., & Bourouiba, L. (2021). How did we get here: what are droplets and aerosols and how far do they go? A historical perspective on the transmission of respiratory infectious diseases. *Interface Focus*, *11*(6). https://doi.org/10.1098/RSFS.2021.0049

Reed, N. G. (2010). The History of Ultraviolet Germicidal Irradiation for Air Disinfection. *Public Health Reports*, *125*(1), 15. https://doi.org/10.1177/003335491012500105

Regev-Yochay, G., Kriger, O., Beni, S., Rubin, C., Mina, M. J., Mechnik, B., … Amit, S. (2021). Real World Performance of SARS-CoV-2 Antigen Rapid Diagnostic Tests in Various Clinical Settings. *MedRxiv*, 2021.03.02.21252400. https://doi.org/10.1101/2021.03.02.21252400

REHVA. (2021). REHVA COVID-19 guidance document How to operate HVAC and other building service systems to prevent the spread of the coronavirus (SARS-CoV-2) disease (COVID-19) in workplaces. *REHVA*. Retrieved from https://www.rehva.eu/fileadmin/user_upload/REHVA_COVID-19_guidance_document_V4.1_15042021.pdf

Rolfsen, B. (2021, June 28). OSHA Virus Rule Intended to Cover All Workers, Draft Shows . Retrieved November 19, 2021, from Bloomberg Law website: https://news.bloomberglaw.com/safety/osha-covid-19-rule-intended-to-cover-all-workers-draft-shows

Saitone, T. L., Aleks Schaefer, K., & Scheitrum, D. P. (2021). COVID-19 morbidity and mortality in U.S. meatpacking counties. *Food Policy*, *101*. https://doi.org/10.1016/J.FOODPOL.2021.102072

Santarpia, J. L., Herrera, V. L., Rivera, D. N., Ratnesar-Shumate, S., Reid, S. P., Ackerman, D. N., … Lowe, J. J. (2021). The size and culturability of patient-generated SARS-CoV-2 aerosol. *Journal of Exposure Science & Environmental Epidemiology 2021*, 1–6. https://doi.org/10.1038/s41370-021-00376-8

Sehgal, N. J., & Milton, D. K. (2021). Applying the Hierarchy of Controls: What Occupational Safety Can Teach us About Safely Navigating the Next Phase of the Global COVID-19 Pandemic. *Frontiers in Public Health*, *9*, 1688. https://doi.org/10.3389/FPUBH.2021.747894/BIBTEX

Smith, C., Odd, D., Harwood, R., Ward, J., Linney, M., Clark, M., … Fraser, L. K. (2021). Deaths in children and young people in England after SARS-CoV-2 infection during the first pandemic year. *Nature Medicine* , 1–8. https://doi.org/10.1038/s41591-021-01578-1

Speake, H., Phillips, A., Chong, T., Sikazwe, C., Levy, A., Lang, J., … McEvoy, S. P. (2020). Flight-Associated Transmission of Severe Acute Respiratory Syndrome Coronavirus 2 Corroborated by Whole-Genome Sequencing. *Emerging Infectious Diseases*, *26*(12), 2872. https://doi.org/10.3201/EID2612.203910

Stabile, L., Pacitto, A., Mikszewski, A., Morawska, L., & Buonanno, G. (2021). Ventilation procedures to minimize the airborne transmission of viruses in classrooms. *Building and Environment*, *202*, 108042. https://doi.org/10.1016/J.BUILDENV.2021.108042

Stockwell, R. ., Wood, M. E., He, C., Sherrard, L. J., Ballard, E. L., & Bell, S. C. (2018). Face masks reduce the release of Pseudomonas aeruginosa cough aerosols when worn for clinically relevant periods. *American Journal of Respiratory and Critical Care Medicine*, *198*(10), 1339–1342. https://doi.org/10.1164/RCCM.201805-0823LE/SUPPL_FILE/DISCLOSURES.PDF

Swadi, T., Geoghegan, J. L., Devine Bsc, T., Mcelnay Msc, C., Mbchb, P. S., Ren Phd, X., … De Ligt, J. (2020). A case study of extended in-flight transmission of SARS-CoV-2 en route to Aotearoa New Zealand. *Science for Communities*. https://doi.org/10.26091/ESRNZ.13257914.V1

Tang, J. W., Bahnfleth, W. P., Bluyssen, P. M., Buonanno, G., Jimenez, J. L., Kurnitski, J., … Dancer, S. J. (2021). Dismantling myths on the airborne transmission of severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2). *The Journal of Hospital Infection*, *110*,

89. https://doi.org/10.1016/J.JHIN.2020.12.022
Tang, J. W., Marr, L. C., & Milton, D. K. (2021). Aerosols should not be defined by distance travelled. *Journal of Hospital Infection*, *115*, 131–132. https://doi.org/10.1016/J.JHIN.2021.05.007
Tang, Julian W., Marr, L. C., Li, Y., & Dancer, S. J. (2021). Covid-19 has redefined airborne transmission. *BMJ*, *373*. https://doi.org/10.1136/BMJ.N913
Taylor, C. A., Boulos, C., & Almond, D. (2020). Livestock plants and COVID-19 transmission. *Proceedings of the National Academy of Sciences of the United States of America*, *117*(50), 31706–31715. https://doi.org/10.1073/PNAS.2010115117/-/DCSUPPLEMENTAL
UNESCO. (2021). Education: From disruption to recovery. Retrieved November 19, 2021, from UNESCO website: https://en.unesco.org/covid19/educationresponse
UNICEF. (2021, March). COVID-19 and School Closures: One year of education disruption - UNICEF DATA. Retrieved November 19, 2021, from UNICEF website: https://data.unicef.org/resources/one-year-of-covid-19-and-school-closures/
US Census Bureau. (2021, March). Tracking Job Losses for Mothers of School-Age Children During a Health Crisis. *US Census Bureau*. Retrieved from https://www.census.gov/library/stories/2021/03/moms-work-and-the-pandemic.html
US Centers for Disease Control and Prevention. (2015, January 13). Hierarchy of Controls . Retrieved November 19, 2021, from US Centers for Disease Control and Prevention website: https://www.cdc.gov/niosh/topics/hierarchy/default.html
US Centers for Disease Control and Prevention. (2021, May 7). Scientific Brief: SARS-CoV-2 Transmission . Retrieved November 19, 2021, from US Centers for Disease Control and Prevention website: https://www.cdc.gov/coronavirus/2019-ncov/science/science-briefs/sars-cov-2-transmission.html
US EPA. (2020). EPA Researchers Study Aerosol Transport and Mitigation Measures to Reduce COVID-19 Transmission . Retrieved November 19, 2021, from https://www.epa.gov/sciencematters/epa-researchers-study-aerosol-transport-and-mitigation-measures-reduce-covid-19
US Occupational Safety and Health Administration. (2021). COVID-19 Healthcare ETS . Retrieved November 19, 2021, from US Occupational Safety and Health Administration website: https://www.osha.gov/coronavirus/ets
Walker, C. M., & Ko, G. (2007). Effect of ultraviolet germicidal irradiation on viral aerosols. *Environmental Science and Technology*, *41*(15), 5460–5465. https://doi.org/10.1021/ES070056U
Wang, C. C., Prather, K. A., Sznitman, J., Jimenez, J. L., Lakdawala, S. S., Tufekci, Z., & Marr, L. C. (2021). Airborne transmission of respiratory viruses. *Science*, *373*(6558). https://doi.org/10.1126/SCIENCE.ABD9149/ASSET/C3B6AAC0-E7B3-43F8-9047-C04940ED3887/ASSETS/IMAGES/LARGE/SCIENCE.ABD9149-F5.JPG
Wood, M. E., Stockwell, R. E., Johnson, G. R., Ramsay, K. A., Sherrard, L. J., Jabbour, N., … Bell, S. C. (2018). Face masks and cough etiquette reduce the cough aerosol concentration of pseudomonas aeruginosa in people with cystic fibrosis. *American Journal of Respiratory and Critical Care Medicine*, *197*(3), 348–355. https://doi.org/10.1164/RCCM.201707-1457OC/SUPPL_FILE/DISCLOSURES.PDF
World Health Organization. (2020a). How is COVID-19 spread and how do you protect yourself

against it? . Retrieved November 19, 2021, from Facebook website: https://www.facebook.com/WHO/videos/507223210199209/

Xu, P., Peccia, J., Fabian, P., Martyny, J. W., Fennelly, K. P., Hernandez, M. T., & Miller, S. L. (2003, August). Efficacy of ultraviolet germicidal irradiation of upper-room air in inactivating airborne bacterial spores and mycobacteria in full-scale studies. Retrieved January 10, 2022, from Atmospheric Environment website: https://www.researchgate.net/publication/238049307_Efficacy_of_ultraviolet_germicidal_irradiation_of_upper-room_air_in_inactivatingairborne_bacterial_spores_and_mycobacteria_in_full-scale_studies

Young, B. C., Eyre, D. W., Kendrick, S., White, C., Smith, S., Beveridge, G., … Peto, T. E. A. (2021). Daily testing for contacts of individuals with SARS-CoV-2 infection and attendance and SARS-CoV-2 transmission in English secondary schools and colleges: an open-label, cluster-randomised trial. *The Lancet*, *398*(10307), 1217–1229. https://doi.org/10.1016/S0140-6736(21)01908-5/ATTACHMENT/6BF50168-4EE8-4899-8381-A2D620738F5D/MMC1.PDF

Zimmerman, K. O., Akinboyo, I. C., Brookhart, ; M Alan, Boutzoukas, A. E., Mcgann, K., Smith, M. J., … Benjamin, D. K. (2021). Incidence and Secondary Transmission of SARS-CoV-2 Infections in Schools. *Pediatrics*. https://doi.org/10.1542/peds.2020-048090