Mini Review

Anna G. Hoover, Wendy Heiger-Bernays, Sweta Ojha and Kelly G. Pennell*

Balancing incomplete COVID-19 evidence and local priorities: risk communication and stakeholder engagement strategies for school re-opening

https://doi.org/10.1515/reveh-2020-0092
Received July 27, 2020; accepted September 8, 2020;
published online October 1, 2020

Abstract: In the midst of the COVID-19 pandemic, United States (U.S.) educational institutions must weigh incomplete scientific evidence to inform decisions about how best to re-open schools without sacrificing public health. While many communities face surging case numbers, others are experiencing case plateaus or even decreasing numbers. Simultaneously, some U.S. school systems face immense infrastructure challenges and resource constraints, while others are better positioned to resume face-to-face instruction. In this review, we first examine potential engineering controls to reduce SARS-CoV-2 exposures; we then present processes whereby local decision-makers can identify and partner with scientists, faculty, students, parents, public health officials, and others to determine the controls most appropriate for their communities. While no solution completely eliminates risks of SARS-CoV-2 exposure and illness, this mini-review discusses engaged decision and communication processes that incorporate current scientific knowledge, school district constraints, local tolerance for health risk, and community priorities to help guide schools in selecting and implementing re-opening strategies that are acceptable, feasible, and context-specific.

***Corresponding author: Kelly G. Pennell**, Department of Civil Engineering, University of Kentucky, College of Engineering, Lexington, KY 40506, USA, E-mail: kellypennell@uky.edu. https://orcid.org/0000-0003-3423-9610
Anna G. Hoover, Department of Preventive Medicine and Environmental Health, University of Kentucky, College of Public Health, Lexington, KY 40506, USA, E-mail: aghoov2@uky.edu
Wendy Heiger-Bernays, Department of Environmental Health, Boston University, School of Public Health, Boston, MA 02118, USA, E-mail: whb@bu.edu
Sweta Ojha, Department of Civil Engineering, University of Kentucky, College of Engineering, Lexington, KY 40506, USA, E-mail: sweta.ojha@uky.edu

Keywords: airborne transmission; children health; COVID-19; indoor air; stakeholder engagement.

Introduction

As U.S. educators in both K-12 and higher education settings prepare to launch a new academic year amidst increasing numbers of SARS-CoV-2 infections in many regions, school leaders critically need a combination of evidence-informed strategies and stakeholder-engaged implementation to reduce morbidity and mortality arising from COVID-19. Schools will resume operations in diverse settings, with many districts facing serious financial constraints and aging buildings, often with sealed windows and sub-optimal ventilation [1]. Absent an effective vaccine or herd immunity, the ability to adhere to public health guidance is a critical consideration for school districts, colleges, and universities evaluating and adapting potential modes of instruction (e.g., remote, online, face-to-face, and/or hybrid). To reduce risk and provide safer educational environments, school leaders therefore need two important kinds of information: (1) which preventive measures can most effectively reduce virus spread in school settings, and (2) how parent, student, faculty, and staff support for implementing preventive measures can best be achieved.

With scientific evidence and non-scientific information rapidly emerging – and at times conflicting – education leaders require environmental and health knowledge to assess new information and adapt it to real-world scenarios. With this information, they can work with local stakeholders to make appropriate evidence-informed, context-specific decisions in a constantly changing information environment. Summarizing relevant bodies of knowledge from engineering and research translation, we provide examples of emerging environmental and engineering controls for SARS-CoV-2 reduction; we then share strategies from stakeholder-engaged environmental health translation that may help education leaders at all levels protect campus communities.

Although the exact implications of school closures and re-openings on community transmission of SARS-CoV-2 are unknown, educational communities are concerned about the impacts of school closures on society, including economics, learning, and mental health. As educational institutions resume instruction, several models have been proposed globally, from reducing class sizes to limiting person-to-person interactions via online instruction to increasing physical distance. Academic calendars have shifted, and extracurricular activities are being re-scheduled or re-configured. Face masks that are required in many public settings are being considered for educational settings. Testing for SARS-CoV-2 viral RNA or antibodies is a component of many school reopening plans [2]. However, many plans do not yet account for the potential role of ventilation, a topic that more than 200 experts [3] recently called on the scientific community to address directly.

The field of environmental health can speak to ventilation issues. With concerns about aersolization of viral particles increasing, environmental health scientists bring knowledge about the importance of exposure pathways and particles that move through airflows. Ventilation highlights just one potentially important yet contentious mitigation approach for which new evidence emerges almost daily [3, 4]. The need for schools to develop ventilation strategies underscores the need for interdisciplinary partnerships with public health officials, scientists, technicians, and lay publics. Effective risk communication can play an important role in clarifying both the challenges and potential solutions.

According to the ASCE Infrastructure Reportcard, 50-million students and 6-million adults occupy 100,000 public schools daily. The quality of U.S. public school facilities rank low (grade of D) and are described as in fair to poor condition [1]. Many more individuals attend private schools and universities with similar infrastructure challenges that have implications for public health. Successfully re-opening schools in the midst of a pandemic requires reaching across educational and scientific communities of practice, as well as affected lay publics, to support meaningful interactions and effective decisions. This mini-review emphasizes that stakeholder engagement must acknowledge community priorities and local tolerance for health risk. We highlight stakeholder engagement and risk communication processes, presenting means by which scientists can identify and collaborate with education leaders to inform decisions that must address finite resources, uncertain science, and community priorities. We discuss stakeholder engagement processes and methods for supporting collaborative sensemaking, building environmental health literacy, recognizing the importance of trust, and sharing critical knowledge to support evidence-informed, stakeholder-engaged strategies for decreasing the spread of SARS-CoV-2.

Discussion

Airborne transmission of SARS-CoV-2

Respiratory viruses follow two major transmission pathways from infectious to susceptible individuals. Infectious individuals can release virus-containing particles of varying dimensions into air, referred to as "aerosols", under several different situations. During breathing, talking, singing and coughing, respiratory, droplets and/or aerosols can be released. Some scientists make distinctions between droplets and aerosols based on size, while others do not. Here, the term aerosol refers to the entire size range released (e.g., 0.1–>100 μm) [5]. Small respirable aerosols of <5–10 μm often follow airflow streams and can travel farther distances, contributing to airborne transmission, but to date it is not feasible to routinely monitor for the presence of viral particles. Larger aerosols >20 μm can travel shorter distances and settle onto surfaces and/or people, potentially exposing susceptible individuals to the virus when they touch these surfaces and then touch their own eyes, nose, or mouth [6, 7]. Growing evidence indicates that SARS-CoV-2 can be transmitted by airborne transmission, large aerosols, and fomites [5, 7], with U.S. Centers for Disease Control and Prevention (CDC) recognizing the importance of airborne transmission [8].

Without a vaccine or highly effective treatments, disease risk reduction requires reducing the probability of exposing susceptible people to the virus. For SARS-CoV-2, increased attention has focused on infected but presymptomatic and asymptomatic individuals who may be responsible for the majority of transmission of COVID-19 to susceptible individuals [3, 7, 9]. As new evidence emerges, debate continues regarding the proportion of cases for which small respirable aerosol (or airbone) transmission is responsible [10]. This debate derives in part because of the lack of studies that directly correlate exposure to persistent airborne virus with disease; however, direct evidence and exposure modeling increasingly suggests airborne transmission is an important and perhaps predominant pathway of SARS-CoV-2 exposure [11–13]. In the absence of consensus on the relative contribution of airborne transmission of SARS-CoV-2, a precautionary approach is important to promote potentially preventive action while encouraging public participation in decisions about prevention strategies. Working from this principle, we turn our attention to mitigation strategies for indoor transmission. Figure 1A illustrates two potential routes of exposure for SARS-CoV-2: inhalational and direct contact. Figure 1B shows that while a mask worn by *either* an infectious or susceptible individual provides limited protection, improved exposure-reducing results are achieved when *both* don masks correctly.

Indoor exposure mitigation strategies for SARS-CoV-2

Adapting the CDC infection control pyramid, Morawska et al. and Deziel et al. summarized methods to minimize indoor exposure to SARS-CoV-2 [4, 14]. Their efforts recognized pathogen elimination as most effective, followed by engineering and administrative controls, with personal protective equipment (PPE) considered least effective. In March 2020, U.S. educational institutions began moving instruction online to eliminate exposure in shared physical spaces. Approximately one month later, the CDC recommended that people wear cloth facemasks as personal protection in public settings where physical distancing could not be ensured. While these strategies met immediate needs at the elimination and PPE ends of the infection control pyramid, they did not directly address the two intermediate mitigation categories: engineering and administrative exposure controls. As schools examine alternatives for Fall 2020 resumption of learning, controls from all four domains will be needed.

Table 1 frames the infection control pyramid set forth by Morawska et al. [4], incorporating specific engineering and administrative controls and recognizing evidence-informed stakeholder engagement as a modulator of effectiveness.

Ventilation: a critical engineering control

While science specific to SARS-CoV-2 transmission is generated and debated, current evidence relies largely on prior studies of related infectious diseases. Morawska et al. discussed the importance of one specific engineering control: ventilation [4]. To account for the evolving science and recommendations, Jimenez developed a tool for estimating SARS-CoV-2 transmission in various educational settings with building ventilation and facemasks [15].

Aerosol transport is significantly influenced by airflow within a building. For large droplets, gravity drives how droplets settle, typically following Stokes Law [16–18], but cross-flows will affect the time and location of where the droplet lands. When a person coughs or sneezes, turbulent gas with suspended aerosols of various sizes are emitted and large droplets will be more influenced by gravity, falling downwards, rather than the turbulent gas emitted. Under these conditions, face shields or vertical partitions may be effective PPE for preventing larger droplets from reaching susceptible individuals [19]; however, respiratory droplets emitting during breathing and talking generally undergo some evaporation during transmission, changing size during transport. Smaller droplets are transported longer distances and will follow airflow patterns, making aerosol transport difficult to predict in a typical building [20] and reducing the effectiveness of face shields and vertical partitions as exposure-preventing PPE [19].

Several research studies have described the role of ventilation and infectious disease transmission (e.g., [21–27]), but these studies have not provided conclusive

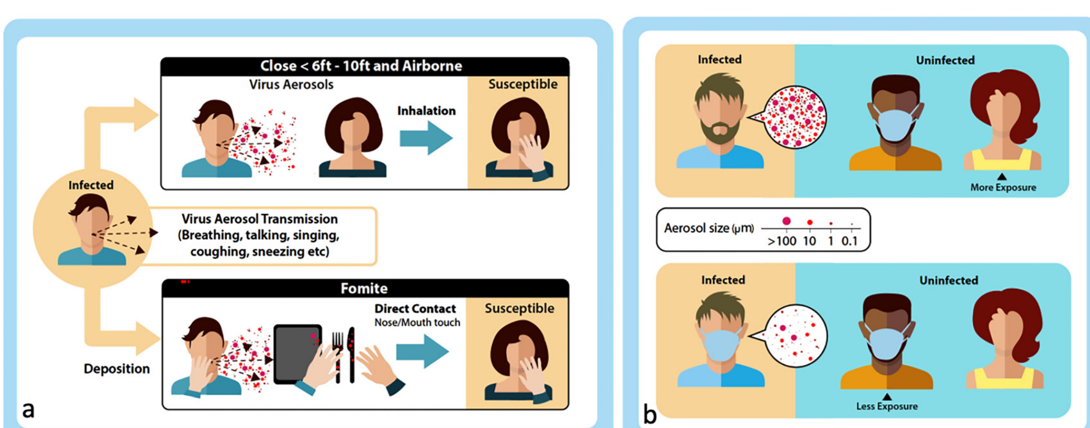

Figure 1: Conceptual model for SARS-CoV-2 aerosol transmission and exposure.

Table 1: Modified infection control pyramid with evidence-based stakeholder engagement.

Traditional effectiveness	Effectiveness modulator	Methods of minimization	Exposure pathway	
			Aerosols	Fomite
Most ↑	↑	Elimination	Physical separation	Disinfection and washing
		Engineering controls	Building ventilation, air purifying devices, plexiglass partitions[a], etc.	Covered surfaces
	Evidence-based Stakeholder Engagement	Administrative controls	Evidence-informed, community-derived enforcement, policies, and risk communication	Evidence-informed, community-derived enforcement, policies, and risk communication
↓ Least	↓	Personal protective equipment	Face masks, face shields[a]	Frequently replacing (e.g., single use) surface and hand coverings

[a]Partitions can be effective for "signaling" to encourage social distancing (e.g., OSHA COVID-19 Retail Worker Guidance: https://www.osha.gov/Publications/OSHA3996.pdf). Both face shields and partitions (e.g., plexiglass) can be useful for reducing exposure to large droplets (e.g., "drops") that result from sneezes or coughs; however, to reduce exposure to smaller aerosols face shields should be worn with a mask. Additionally, partitions placed within rooms impact airflows and their effect on aerosol transport should be carefully evaluated because reduction in aerosol exposure may not occur if aerosols are concentrated near or around the partition (and humans).

information about the optimal number of air changes per hour, or ACH, for the highly variable types of buildings encountered in educational settings. Predicting adequate ventilation rates to prevent infectious disease transmission is complex, in part due to the location of the source (infectious person), number of virions per unit of air, and incomplete mixing, which results in aerosol concentrations varying substantially throughout an enclosed space. Variability of ventilation systems and building geometries adds even more complexity. Ventilation includes natural ventilation and mechanical ventilation; and can be highly variable depending on a range of factors [4, 28] including occupant behavior in buildings. Natural ventilation is outdoor airflow through intentional openings such as open windows and is driven by weather and building conditions (e.g., temperatures and pressure gradients), making airflow patterns unpredictable and variable [28].

While additional research is needed to better understand the complexity of airflows and building ventilation systems, increasing building ACH appears potentially beneficial for decreasing airborne virus accumulation. This strategy could be implemented as an engineering control to reduce the spread of SARS-CoV-2. The Jimenez tool provides guidance for how to make professional judgments about increasing building ventilation [15]; however, ASHRAE [28] and Morawska et al. [4] provide realistic constraints for stakeholders engaged in building management decisions to consider. Carbon dioxide (CO_2) levels within occupied buildings are used as a surrogate for air exchange. People produce CO_2 when they exhale; therefore, the more people in the room, the more CO_2 is produced. CO_2 levels between 300 and 600 are found in outdoor air, and levels below 800 ppm are being used as an indicator of ventilation adequacy in schools [28, 29]. However, direct evidence for sufficiency of SARS-CoV-2 dilution is lacking. Ventilating spaces with outdoor air instead of circulating untreated indoor air can efficiently increase ventilation. Air treatment devices (e.g., ultraviolet [UV] radiation in the germicidal range may be potentially effective for SARS-CoV-2 based on its effectiveness for other viruses) [30] and/or air filtration using adequate particle filter sizes [31] are additional engineering controls for decreasing SARS-CoV-2 exposure risks. Wearing cloth face masks indoors adds an important layer of protection against the exposure of SARS-CoV-2 to susceptible individuals. However, masks vary widely in efficacy, due in part to the types of material, the fit of the mask and the propensity for removal by the wearer [32]; as such, they do not meet the rigorous NIOSH definition of PPE. Figure 2 illustrates the potential role of ventilation in modulating SARS-CoV-2 exposure in classrooms. Recirculating ventilation systems in rooms with closed windows limit outside airflows and create the greater potential exposure risks. Conversely, ventilation systems that both use outside (rather than recirculating) air and open windows potentially reduce the airborne presence of SARS-CoV-2 within the classroom but may introduce additional pollutants, depending upon where the school is located. In addition, increasing ventilation by using outdoor air will result in hotter, more humid classrooms in fall and spring and colder, dryer classrooms in the winter.

Risk communication: a key administrative control

To ensure people know when, where, and how to implement engineering controls, it is critical to engage stakeholders in developing strategies, obtaining data, and

Figure 2: Ventilation and exposure scenarios.
Notes: Outdoor air flows into and out of windows due to indoor–outdoor temperature/pressure differences. Top panel has “more” exposure, middle and bottom panel have “less” exposure than top panel.

creating effective risk messages. The emergence of SARS-CoV-2 and the subsequent COVID-19 pandemic have left scientists and public health officials across disciplines playing catch-up in terms of characterizing and reducing transmission risk. Consequently, public health professionals are even further behind in developing and messaging best practices for prevention. Resulting uncertainty can influence risk perceptions among stakeholders, from lay publics to regulatory officials [33], and contribute to competing risk narratives [34]. Under these circumstances, effective translation of science to public health action requires clear risk messaging about both the nature of SARS-CoV-2 transmission and protective steps for decreasing exposures to the virus.

“Research translation” describes the timely and efficient transfer of scientific findings into improvements in public health outcomes [35]. Conceptualizations of translation have evolved over time, from a three-step process of information diffusion, targeted dissemination, and implementation [36] to the National Institute of Environmental Health Sciences Translational Research Framework, which depicts five concentric rings moving from scientific discovery through application and synthesis, implementation and adjustment, and practice, ultimately resulting in positive health impacts [37].

The COVID-19 pandemic’s unique combination of global public health emergency, pre-print and open-access scientific publishing, often contradictory drivers of economic imperatives and public health protection, and widespread interest from social and traditional media has created a perfect storm of uncertainty by truncating what is traditionally a years- (if not decades-) long translational process [38–40]. Basic scientific discovery about the virus and its transmission occurs nearly simultaneously with all other stages of the translation process. Rather than being vetted, synthesized, and replicated, SARS-CoV-2 and COVID-19 findings are disseminated immediately to hyper-interested publics. Instead of working with scientists to develop and test tools and interventions before widespread implementation, public health and regulatory officials must adopt policies and urge behaviors even as the body of supporting evidence is debated. These debates, along with the need to change guidance as new knowledge emerges, further contribute to public confusion.

Shifting messages from national and international public health organizations on issues related to masking [41], asymptomatic transmission of the virus [42], and airborne transmission, along with misinformation about the pandemic [43], have contributed to individual and organizational uncertainty about the appropriate preventive actions to take. Further, adherence to expert COVID-19 prevention recommendations is mediated by many factors, including political partisanship [44] and message framing [45]. Together, these challenges can result in public outrage overtaking efforts to manage SARS-CoV-2 exposure risks [46]. Deploying effective risk communication to refocus attention toward transmission hazards is a critical administrative control for educational institutions returning to a “new normal”.

Translational and messaging challenges are not new for environmental health scientists who work with hazardous waste sites that often require decades to remediate; therefore, research translation specialists and public health scientists in environmental health research centers could prove useful partners for overburdened school leaders trying to manage information. During site remediation periods, at-risk residents receive sometimes-conflicting information from diverse governmental, private, and nonprofit organizations. When these mixed environmental health messages collide with confusion about organizational roles, trust in technical expertise can deteriorate [47]. The resulting distrust can exacerbate challenges for building environmental health literacy (EHL), the knowledge and skills people and communities need to take health-protective actions [48–50]. Building EHL among school stakeholders can improve scientific understanding of potential challenges and solutions for creating safer back-to-school plans.

To tackle low levels of trust and build EHL, research translation professionals increasingly turn to participatory approaches that encourage co-learning while empowering at-risk communities [50–53]. These engaged approaches are consistent with the precautionary principle, foregrounding community values and incorporating stakeholder perspectives into prevention strategies and risk messages that are both evidence-based and feasible [54, 55]. Engaged approaches can build trust among stakeholders while encouraging contextual adaptations that improve both the validity and fit of interventions [56]. When developing and implementing COVID-19 prevention strategies and risk communication, educational institutions need to build trust among stakeholders while ensuring policies, practices, and messages are appropriate for specific settings. But how can educational leaders systematically identify and engage their stakeholders – particularly when the timeline for decision-making is days, rather than months or years?

Modulating effectiveness of controls: stakeholder identification and engagement

In the broadest sense, "stakeholders" are individuals and groups who have "legitimate interests in procedural and/or substantive aspects of [organizational] activity" [50]. These interests sometimes are divided into primary and secondary stakeholder categories, based on the nature of organizational claim or interest [57]. Within an educational institution, *primary stakeholders* include students, faculty, staff, and administrators. *Secondary stakeholders* often depend upon the type of educational organization; for example, K-12 organizations must consider the needs and concerns of parents and boards of education, while colleges and universities connect regularly with alumni and other donors. Successful risk communication with both primary and secondary stakeholders requires determining who has a legitimate stake in organizational activity and identifying key stakeholder representatives who can assist organizational leaders in understanding diverse information needs and preferences. By ensuring school stakeholders have a voice in developing and implementing COVID-19 risk-reducing strategies, local leaders can build local support for and improve the feasibility of those strategies.

Again, lessons from the field of environmental health can inform the application of stakeholder-engaged approaches in risk reduction. In recent years, stakeholder engagement projects and studies have assisted in building EHL [51], improving report-back of personal exposure data [58], exploring local environmental health disparities [59], and reducing or preventing exposures [60]. Environmental public health scientists and research translation specialists therefore could prove valuable partners not only in risk communication, but also in helping overburdened school officials successfully select and implement stakeholder engagement processes.

A number of approaches have emerged that can help educational leaders and their partners identify and prioritize stakeholders in the engagement process. The social-ecological model, for example, provides one high-level framework for identifying stakeholders within key five key spheres of influence: policy, community, organizational, interpersonal, and individual [61]. Which spheres are most important for prioritizing strategies to reduce the spread of SARS-CoV-2 within educational institutions? Who are the key stakeholders within each priority sphere?

After high-level stakeholders have been identified, the Alignment, Influence, and Interest Matrix, or AIIM [62], can provide a complementary second step to prioritizing the engagement of specific stakeholders who can help prevent SARS-CoV-2 transmission on campuses. AIIM classifies potential stakeholders as "high" or "low" across two dimensions: alignment and interest (see Figure 3). By placing stakeholders in the appropriate cells of this matrix, organizations can better target risk messages, thereby improving their effectiveness with key constituencies. Alignment indicates the extent to which a stakeholder shares objectives and perspectives with the organization, while interest indicates a stakeholder's attention and commitment to the issue at hand. Different communication strategies are appropriate for stakeholders within each cell of the matrix. Where both alignment and interest are high, the organization may deploy messages that stress co-learning about prevention; however, where the stakeholder lacks both alignment and interest, the organization will need messaging that strives to develop stakeholder awareness of and enthusiasm for COVID-19 prevention strategies. Where interest is high but alignment is low, messages may need to challenge stakeholder beliefs, while high-alignment/low-interest stakeholders may require messages that raise perceived salience of COVID-19 prevention. Fully engaging partners, or key informants, who represent each cell of the matrix will help educators ensure that prevention messages effectively target each audience.

One example of an opportunity for AIIM-informed stakeholder engagement is ventilation of schools by incorporating resources from ASHRAE [28]. School principals, college deans, and other senior administrators likely are highly aligned with and interested in reducing SAR-CoV-2 exposures throughout their school populations. However, once decisions have been made to increase outdoor ventilation rates, additional stakeholders – including facility/building operations personnel, public health scientists, and other individuals with indoor air quality knowledge – likely would be most aligned with and interested in carrying out the next set of objectives toward increasing and maintaining building ventilation rates. These stakeholders would evaluate guidance from organizations, such as ASHRAE, which requires knowledge of ventilation standards and codes. At each step of the process, new objectives may emerge and new stakeholders need be identified so that the process can be most effectively influenced.

Identifying key informants and opinion leaders within stakeholder groups can be challenging. Social network analysis, or SNA, offers a potential third step toward further prioritizing candidates to engage in developing COVID-19 prevention strategies [63]. Social network theory illustrates the types of social ties that exist among individuals and organizations, emphasizing the importance of structure and placement of an individual within that structure [64]. In SNA, an individual's connections to other individuals are depicted as ties. When the number of ties within a personal network is examined, a snapshot of that person's sphere of influence emerges. Many ties – especially ties to other people with numerous connections themselves – can indicate a person's centrality within a network. Such individuals may be important influencers within their organizational or social spheres; therefore, they could be critical partners in devising and disseminating effective risk messages within their networks.

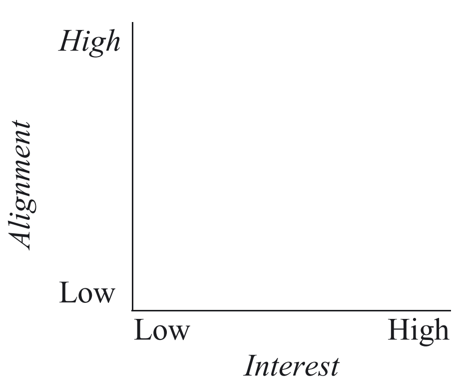

Figure 3: The alignment, influence, and interest matrix (AIIM).

As plans unfold for the coming school year, school systems struggle to balance SARS-CoV-2 exposure control measures with the reality of over-crowded classrooms, inadequately maintained school buildings, and parents who need their children back in the classroom, highlighting the need for expertise by trusted stakeholders as critical partners. Massachusetts released its "Initial Fall Reopening Guidance" on June 25, 2020, requiring school systems develop three learning plans – virtual, hybrid, and fully in-person, where students and staff maintain social distances of three to six feet, wear face-masks (grades 2–12), and "consider" increasing ventilation [65]. The guidance sets the expectation that children need to be back in school this fall, while minimizing risk of contracting COVID-19. In at least one community, data from a preliminary survey of parents, teachers, and staff regarding their learning-plan preferences were coupled with interpretation of current COVID-19 exposure and risk science, leading to the release of a plan that did not include the full in-person option [66]. In consultation with local public health officials, stricter guidelines than those required by the state were proposed – namely the use of 6-foot distancing and masks for pre-K-12, as well as explicit consideration of understanding the schools' ventilation systems and formal recognition of the need for engineering controls. In this case, local public health authorities used emerging SARS-CoV-2 science to support a more restrictive return to school plan. The Massachusetts example illustrates that schools and communities partnering with knowledgeable scientific experts can create the opportunity for more data-driven local decisions that can both influence and educate.

After education leaders identify stakeholders and key informants, they will need to leverage stakeholder knowledge both to prioritize COVID-19 prevention strategies and to create and disseminate messages that encourage widespread strategy adoption. Fischhoff has described the evolution of risk communication as shifting from unidirectional and information-driven activities to a kind of partnership development [67]. Such partnerships are particularly important for addressing COVID-19 risk, which already is deeply embedded in subjectivity and the social construction of risk [68, 69]. Numerous tools and approaches can help optimize stakeholder engagement activities. Community-based participatory communication [70], collaborative and participatory modeling [71], community-based participatory research [72, 73], and the convergence-building model of environmental health communication [74] all describe group processes for stakeholder-engaged research, translation, and/or communication.

Education leaders can select and adapt the engagement strategies that work best for their settings and populations. Third-party knowledge from industrial hygienists, public health officials, engineers, and other technical experts can help balance power dynamics within these collaborative spaces while also increasing environmental health literacy among participants. Multiple voices representing different backgrounds and organizational stakes can increase capacity for successfully reducing COVID-19 spread by decreasing the likelihood that educational leaders will become trapped in a single set of expectations. Recognition of the need for institutional and engineering controls to reduce SARS-CoV-2 exposure is rapidly expanding, as evidenced by a group of parents drafting a template for others to use in advocating for safe re-opening of schools [75]. In short, participatory communication approaches can help address innovation-limiting constraints on sensemaking [76, 77].

Conclusions

Scientists and public health organizations continue to debate the role of the aerosol transport in SARS-CoV-2 transmission. With high levels of uncertainty and potentially severe outcomes related to COVID-19, leaders wishing to resume educational operations will need to generate evidence-informed policies that combine scientific analysis and precautionary measures [78]. As Greenhalgh and colleagues have argued, "in the face of a pandemic the search for perfect evidence may be the enemy of good policy" [79].

Using the infection control pyramid, evidence-informed COVID-19 precautionary policies were implemented in many areas of the U.S. beginning in March 2020. Physical distancing addresses the need for elimination controls, and widespread masking supports personal protective controls. Opportunities remain for more robust incorporation of engineering and administrative controls in multi-tier COVID-19 prevention.

In this mini-review, we discuss ventilation as a potentially valuable engineering control for educational institutions preparing to resume operations. In schools where ventilation can be increased through open windows or where air treatment (Figure 2) can be placed in air handling devices, opportunities exist to reduce the presence of and subsequent exposure to SARS-CoV-2. Critically, ventilation to reduce the spread of SARS-CoV-2 must include fresh outdoor air, not merely the circulation of unfiltered indoor air from other rooms [3]. Existing resources (e.g., [28, 80, 81]) can help guide decision makers on how to promote healthier indoor environments Emerging COVID-19 science necessitates that stakeholders remain engaged with experts to inform critical decisions.

We also position risk communication as a key administrative control that allows education leaders, faculty, students, parents, and public health professionals to share evidence and rationale for local strategy selection and implementation. Unfortunately, the emerging nature of pandemic-related scientific evidence has contributed to mixed and changing messages from public health officials. Both scientific uncertainty and shifting risk communication can foment confusion and distrust among publics [82]; therefore, we argue for stakeholder engagement as a potentially important modulator of the effectiveness of controls. We examine ways in which leaders can identify key stakeholders to build collaborative prevention and mitigation approaches and messaging (Figure 3). Stakeholder-engaged strategies also answer calls for more inclusive COVID-19 prevention strategies and messaging [83]. Participatory engagement approaches that are designed to build trust and include diverse perspectives can help ensure the real-world feasibility of evidence-informed prevention strategies while also improving messaging to students, faculty, staff, parents, and other stakeholders [53].

In addition to re-opening strategies, it is imperative to discuss local tolerance for COVID-19 cases in the classroom or institution. While case numbers may be limited through exposure controls, at some point the numbers are likely to increase. The data on case numbers depends on sufficient community COVID-19 testing and contact tracing capabilities. As with any other environmental health risk situation, communities must decide how much risk is too much, and in the case of COVID-19, how many cases are too many in one school?

Amidst changing messages and emerging science, educational leaders following the precautionary principle should consider implementing ventilation strategies that can mitigate disease transmission. Even the best strategies, however, are only as good as organizations' and individuals' willingness to use them. Effective implementation requires partnerships among educators, students, parents, engineers, risk communicators, and other key stakeholders to ensure optimal prevention and save lives on campuses.

As educational institutions resume on-campus activities, many are publicly documenting their decision and implementation processes. It will be important to analyze stakeholder compliance with prevention strategies, as well as the overall effectiveness of those strategies, to encourage future examination of the potential mediating role of stakeholder engagement on the efficacy of communication, adoption, and, ultimately, prevention.

Research funding: The project described is supported by University of Kentucky Superfund Research Program Grant P42 ES007380, the Boston University Superfund Research Program Grant P42 ES007381, by UK-CARES Grant P30 ES026529 from the National Institute of Environmental Health Sciences, by Grant Number 1452800 from the National Science Foundation, and by Award Number G08LM013185 from the National Library of Medicine. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institute of Environmental Health Sciences, National Library of Medicine or the National Science Foundation.
Author contributions: All authors have accepted responsibility for the entire content of this manuscript and approved its submission.
Competing interests: None declared.

References

1. American Society of Civil Engineers (ASCE). America infrastructure report card; 2017.
2. Guthrie BL, Tordoff DM, Meisner J, Tolentino L, Jiang W, Fuller S, et al. Summary of school re-opening models and implementation approaches during the COVID-19 pandemic; July 6, 2020.
3. Morawska L, Milton DK. It is time to address airborne transmission of COVID-19. Clin Infect Dis 2020. https://doi.org/10.1093/cid/ciaa939.
4. Morawska L, Julian WT, William B, Philomena MB, Atze B, Giorgio B. How can airborne transmission of COVID-19 indoors be minimised? 2020.
5. Allen J., Marr L. Re-thinking the potential for airborne transmission of SARS-CoV-2 2020. https://doi.org/10.20944/preprints202005.0126.v1.
6. Tellier R, Li Y, Cowling BJ, Tang JW. Recognition of aerosol transmission of infectious agents: a commentary. BMC Infect Dis 2019;19:101.
7. Prather KA, Wang CC, Schooley RT. Reducing transmission of SARS-CoV-2. Science 2020. https://doi.org/10.1126/science.abc6197.
8. Centers for Disease Control (CDC). How COVID-19 spreads; 2020. Available from: https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/how-covid-spreads.html [Accessed 14 Sep 2020].
9. Moghadas SM, Meagan CF, Pratha S, Abhishek P, Affan S, Burton H, et al. The implications of silent transmission for the control of COVID-19 outbreaks. Proc Natl Acad Sci USA 2020. https://doi.org/10.1073/pnas.2008373117.
10. World Health Organization (WHO). Transmission of SARS-CoV-2: implications for infection prevention precautions; 9 July 2020.
11. Lednicky JA, Lauzardo M, Fan ZH, Jutla AS, Tilly T, Gangwar M, et al. Viable SARS-CoV-2 in the air of a hospital room with COVID-19 patients. medRxiv. https://doi.org/10.1101/2020.08.03.20167395.
12. Azimi P, Keshavarz Z, Guillermo J, Laurent C, Stephens BR, Allen JG, et al. Mechanistic transmission modeling of COVID-19 on the diamond princess cruise ship demonstrates the importance of aerosol transmission. medRxiv. https://doi.org/10.1101/2020.07.13.20153049.
13. Jones RM. Relative contributions of transmission routes for COVID-19 among healthcare personnel providing patient care. J Occup Environ Hyg 2020. https://doi.org/10.1080/15459624.2020.1784427.
14. Deziel NC, Allen JG, Scheepers PTJ, Levy JI. The COVID-19 pandemic: a moment for exposure science. J Expo Sci Environ Epidemiol 2020: 1–3. https://doi.org/10.1038/s41370-020-0225-3.
15. Jimenez J-L, New model estimates COVID-19 transmission in classrooms, buses, protests, more, in Cooperative Institute for Research in Environmental Sciences at the University of Colorado Boulder; June 25, 2020.
16. Xie X, Li Y, Chwang AT, Ho PL, Seto WH. How far droplets can move in indoor environments–revisiting the Wells evaporation–falling curve. Indoor Air 2007;17:211–25.
17. Li Y, Leung GM, Tang JW, Yang X, Chao CYH, Lin JZ, et al. Role of ventilation in airborne transmission of infectious agents in the built environment – a multidisciplinary systematic review. Indoor Air 2007;17:2–18.
18. Jones RM, Brosseau LM. Aerosol transmission of infectious disease. J Occup Environ Med 2015;57:501–8.
19. Roberge RJ. Face shields for infection control: a review. J Occup Environ Hyg 2016;13:235–42.
20. Jayaweera M, Perera H, Gunawardana B, Manatunge J. Transmission of COVID-19 virus by droplets and aerosols: a critical review on the unresolved dichotomy. Environ Res 2020; 188:109819–19.
21. Artenstein MS, Miller WS, Rust JH Jr, Lamson TH. Large-volume air sampling of human respiratory disease pathogens. Am J Epidemiol 1967;85:479–85.
22. Booth TF, Kournikakis B, Bastien N, Ho J, Kobasa D, Stadnyk L, et al. Detection of airborne severe acute respiratory syndrome (SARS) coronavirus and environmental contamination in SARS outbreak units. J Infect Dis 2005;191: 1472–7.
23. Chen P-S, Li C-S. Concentration profiles of airborne *Mycobacterium tuberculosis* in a hospital. Aerosol Sci Technol 2008;42:194–200.
24. Sawyer MH, Chamberlin CJ, Wu YN, Aintablian N, Wallace MR. Detection of varicella-zoster virus DNA in air samples from hospital rooms. J Infect Dis 1994;169:91–4.
25. Huynh KN, Oliver BG, Stelzer S, Rawlinson WD, Tovey ER. Detection of varicella-zoster virus DNA in throat swabs of patients with herpes zoster and on air purifier filters. J Med Virol 2002;66: 567–70.
26. Mastorides SM, Oehler RL, Greene JN, Sinnott JT 4th, Kranik M, Sandin RL. The detection of airborne *Mycobacterium tuberculosis* using micropore membrane air sampling and polymerase chain reaction. Chest 1999;115:19–25.
27. Huynh KN, Oliver BG, Stelzer S, Rawlinson WD, Tovey ER. A new method for sampling and detection of exhaled respiratory virus aerosols. Clin Infect Dis 2008;46:93–5.
28. ASHRAE, Technical Resource. Reopening of schools and resources. Available from https://www.ashrae.org/technical-resources/reopening-of-schools-and-universities [Accessed 17 Aug 2020].

29. ACGIH. Industrial ventilation a manual of recommended practice, 23rd ed. Cincinnati, OH: American Conference of Governmental Industrial Hygienists; 1998.
30. Kujundzic E, Matalkah F, Howard CJ, Hernandez M, Miller SL. UV air cleaners and upper-room air ultraviolet germicidal irradiation for controlling airborne bacteria and fungal spores. J Occup Environ Hyg 2006;3:536–46.
31. Azimi P, Zhao D, Stephens B. Estimates of HVAC filtration efficiency for fine and ultrafine particles of outdoor origin. Atmos Environ 2014;98:337–46.
32. Fischer EP, Fischer MC, Grass D, Henrion I, Warren WS, Westman E, et al. Low-cost measurement of facemask efficacy for filtering expelled droplets during speech. Sci Adv. https://doi.org/10.1101/2020.06.19.20132969.
33. Heath RL, Bradshaw J, Lee J. Community relationship building: local leadership in the risk communication infrastructure. J Publ Relat Res 2002;14:317–53.
34. Sellnow TL, Sellnow DD, Helsel EM, Martin JM, Parker JS. Risk and crisis communication narratives in response to rapidly emerging diseases. J Risk Res 2019;22:897–908.
35. Cochrane LJ, Olson CA, Murray S, Dupuis M, Tooman T, Hayes S, et al. Gaps between knowing and doing: understanding and assessing the barriers to optimal health care. J Continuing Educ Health Prof 2007;27:94–102.
36. Lomas J. Diffusion, dissemination, and implementation: who should do what?. Ann N Y Acad Sci 1993;703:226–35. discussion 235.
37. Pettibone KG, Balshaw DM, Dilworth C, Drew CH, Hall JE, Heacock M, et al. Expanding the concept of translational research: making a place for environmental health sciences. Environ Health Perspect 2018;126:074501.
38. Balas EA, Boren SA. Managing clinical knowledge for health care improvement. In: Bemmel J, McCray AT, editors Yearbook of medical informatics; 2000:65–70 pp, vol. 9.
39. Berwick DM. Disseminating innovations in health care. JAMA 2003;289:1969–75.
40. Morris ZS, Wooding S, Grant J. The answer is 17 years, what is the question: understanding time lags in translational research. J R Soc Med 2011;104:510–20.
41. Farr C, Why scientists are changing their minds and disagreeing during the coronavirus pandemic. 2020, 23 May.
42. Wan W, Berger M, Are asymptomatic people spreading the coronavirus? A WHO official's words spark confusion, debate. in Washington Post. 2020.
43. Garrett L. COVID-19: the medium is the message. Lancet 2020; 395:942–3.
44. Grossman G, Kim S, Rexer J, Thirumurthy H, Political partisanship influences behavioral responses to governors' recommendations for COVID-19 prevention in the United States. Available at SSRN 3578695, 2020.
45. Everett JAC, Colombatto C, Chituc V, Brady WJ, Crockett M. The effectiveness of moral messages on public health behavioral intentions during the COVID-19 pandemic. PsyArXiv Preprint 2020. https://doi.org/10.31234/osf.io/9yqs8.
46. Sandman PM, Covello VT, McCallum DB, Pavlova MT. Hazard versus outrage in the public perception of risk. In: Effective risk communication. Boston, MA: Springer; 1989:45–9 pp.
47. Hoover AG. Sensemaking, stakeholder discord, and long-term risk communication at a US Superfund site. Rev Environ Health 2017;32:165–9.
48. Finn S, O'Fallon L. The emergence of environmental health literacy—from its roots to its future potential. Environ Health Perspect 2017;125:495–501.
49. Gray KM. From content knowledge to community change: a review of representations of environmental health literacy. Int J Environ Res Publ Health 2018;15:466.
50. Hoover AG. Defining environmental health literacy. In: Finn S, O'Fallon L, editors. Environmental health literacy. Cham, Switzerland: Springer; 2019:3–18. https://doi.org/10.1007/978-3-319-94108-0.
51. Madrigal DS, Minkler M, Parra KL, Mundo C, Gonzalez JEC, Jimenez R, et al. Improving Latino youths' environmental health literacy and leadership skills through participatory research on chemical exposures in cosmetics: the HERMOSA study. Int Q Community Health Educ 2016;36:231–40.
52. Davis LF, Ramirez-Andreotta MD, McLain JET, Kilungo A, Abrell L, Buxner S, et al. Increasing environmental health literacy through contextual learning in communities at risk. Int J Environ Res Publ Health 2018;15:2203.
53. Hoover AG, Koempel A, Christian WJ, Tumlin KI, Pennell KG, Evans S, et al. Appalachian environmental health literacy: building knowledge and skills to protect health. J Appalachian Health 2020;2:47.
54. Dagron G. Making waves: stories of participatory communication for social change: participatory communication case studies. Rockefeller Foundation; 2001.
55. Carey JW. Technology and ideology: the case of the telegraph. Communication as culture: essays on media and society; 1989: 201–30 pp.
56. Wallerstein N, Duran B. Community-based participatory research contributions to intervention research: the intersection of science and practice to improve health equity. Am J Public Health 2010;100:S40–6.
57. Clarkson ME. A stakeholder framework for analyzing and evaluating corporate social performance. Acad Manag Rev 1995; 20:92–117.
58. Haynes EN, Elam S, Burns R, Spencer A, Yancey E, Kuhnell P, et al. Community engagement and data disclosure in environmental health research. Environ health perspect 2016 Feb;124:A24–7.
59. Brandt HM, Haynes VE, Rice LJ, Campbell D, Williams E, Glover SH, et al. photovoice as a tool for community engagement to assess the environment and explore environmental health disparities. J Health Dispar Res Pract 2017;10:6.
60. Trottier BA, Carlin DJ, Heacock ML, Henry HF, Suk WA. The importance of community engagement and research translation within the NIEHS Superfund research program. Int J Environ Res Publ Health 2019;16:3067.
61. Lee BC, Bendixsen C, Liebman AK, Gallagher SS. Using the socio-ecological model to frame agricultural safety and health interventions. J Agromed 2017;22:298–303.
62. Mendizabal E. The alignment, interest and influence matrix (AIIM) guidance note. London: ODI Manual/ToolkitODI; 2010. Available from: https://www.odi.org/sites/odi.org.uk/files/odi-assets/publications-opinion-files/6509.pdf.
63. Valente TW, Palinkas LA, Czaja S, Chu K-H, Brown CH. Social network analysis for program implementation. PLoS One 2015; 10:e0131712.
64. Borgatti SP, Mehra A, Brass DJ, Labianca G. Network analysis in the social sciences. Science 2009;323:892–5.
65. Riley, JC, Initial fall school reopening guidance. June 25, 2020.

66. Hackett J. Lexington back-to-school blueprint. Google document. Available from: https://docs.google.com/document/d/1T7iRDGbB5cuzqWsJbWJtdTUiEa1dO3BOIFhpW0sclW8/edit [Accessed 14 Jul 2020].
67. Fischhoff B. Risk perception and communication unplugged: twenty years of process 1. Risk Analysis 1995;15:137–145.
68. Boholm Å. Speaking of risk: matters of context. Environ Commun 2009;3:335–54.
69. Heath RL, O'Hair HD. The significance of crisis and risk communication. Handbook of risk and crisis communication; 2009:5–30 pp.
70. Anyaegbunam C, Hoover A, Schwartz M. Use of community-based participatory communication to identify community values at a Superfund site. In: World environmental and water resources congress 2010: challenges of change; 2010.
71. Basco-Carrera L, Warren A, van Beek E, Jonoski A, Giardino A. Collaborative modelling or participatory modelling? A framework for water resources management. Environ Model Software 2017; 91:95–110.
72. Becker AB, Israel BA, Allen A. Strategies and techniques for effective group process in CBPR partnerships. In: Methods in community-based participatory research for health; 2005, vol. 2: 69–94 pp.
73. Winterbauer NL, Bekemeier B, VanRaemdonck L, Hoover AG. Applying community-based participatory research partnership principles to public health practice-based research networks. SAGE Open 2016;6. https://doi.org/10.1177/2158244016679211.
74. Hoover AG. Communication at superfund sites and the reification of division: toward a convergence-building model of risk communication; 2013.
75. Collins A. Parent letter template—we demand safe schools! 2020. Available from: https://sfpsmom.com/parent-letter-template-we-demand-safe-schools/ [Accessed 14 Jul 2020].
76. Weick KE. Enacted sensemaking in crisis situations. J Manag Stud 1988;25:305–17.
77. Weick K. Sensemaking in organizations. Thousand Oaks, CA: Sage Publications; 1995.
78. Aven T, Bouder F. The COVID-19 pandemic: how can risk science help? J Risk Res 2020:1–6. https://doi.org/10.1080/13669877.2020.1756383.
79. Greenhalgh T, Schmid MB, Czypionka T, Bassler D, Gruer L. Face masks for the public during the COVID-19 crisis. BMJ 2020:369.
80. Jones E, Young A, Clevenger K, Salimifard P, Wu E, Lahaie LM, et al. Healthy schools: risk reduction strategies for reopening schools. Harvard TH Chan School of Public Health Healthy Buildings Program; 2020.
81. United States Environmental Protection Agency (USEPA). EPA supports healthy indoor environments in schools during COVID-19 pandemic. Available from: https://www.epa.gov/iaq-schools/epa-supports-healthy-indoor-environments-schools-during-covid-19-pandemic [Accessed 14 7 2020].
82. Betsch C, Wieler LH, Habersaat K. Monitoring behavioural insights related to COVID-19. Lancet 2020;395:1255–6.
83. Berger ZD, Evans N, Phelan AL, Silverman RD. COVID-19: control measures must be equitable and inclusive. BMJ 2020. https://doi.org/10.1136/bmj.m1141.