Prioritising indoor air quality in building design can mitigate future airborne viral outbreaks

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Abstract:

The ongoing COVID-19 pandemic has brought into focus how poor indoor air quality can amplify the effects of airborne viruses. Rather than promoting health and wellbeing, our built environment often worsens air quality through inadequate ventilation, air recirculation, material specification and the additional pollution load from mechanical heating and cooling. In this think-piece, we introduce a selection of interrelated building design strategies to improve indoor air quality and reduce the spread and impact of airborne disease. We also highlight the need for interdisciplinary collaboration, targeted policy change and leadership on air quality to build resilience against future airborne viral outbreaks.

While much of the world is self-isolating at home, the COVID-19 pandemic has brought into focus the adverse effects that the built environment can have on our health, especially due to poor indoor air quality. It is currently understood that the COVID-19 virus is spread via respiratory droplets which appear to have a higher stability in indoor air, when compared to outdoor air[i], and that high levels of common indoor pollutants strongly promote COVID-19 transmission[ii]. Poor indoor air quality, stemming from both indoor sources and the ingress of outdoor pollutants, is worsened by inadequate ventilation, lack of air filtration and air recirculation within enclosed spaces. These factors can, therefore, be the difference between containing the spread of a novel coronavirus and the infection of an entire building. Instead of integrating healthy indoor air quality strategies into the design of a building, complex Heating, Ventilation and Air Conditioning (HVAC) systems are commonly added in the latter stages of the design process to control the characteristics of indoor air, and generally prioritise thermal comfort above the occupant's health.

The significant drop in the level of some outdoor air pollutants seen during the COVID-19 economic shutdown highlights how polluted the ambient air in our cities has become. High ambient air pollution is tightly associated with increased COVID-19 transmission[ii], decreased lung function and greater risk of developing chronic respiratory diseases, such as Chronic Obstructive Pulmonary Disease (COPD) and asthma[ii, iii]. It is also becoming evident that the impact of COVID-19 is much greater for those with existing health conditions or a weakened immune system. The combination of high ambient air pollution levels and a novel coronavirus, therefore, puts a population at greater risk. This is supported by past studies which have drawn a correlation between high ambient air pollution levels and increased mortality rates from diseases caused by other coronaviruses, such as Severe Acute Respiratory Syndrome (SARS)[iii]. Concerningly, it has often been found that pollutant concentrations are higher in indoor air than outdoor air, owing to activities such as cooking indoors[iv]. Therefore, strategies to improve the quality of indoor air must be prioritised alongside those to improve ambient air quality at an urban scale to reduce a population's risk factors when confronted with a novel airborne virus, such as SARS-CoV-2.

Adequate ventilation, air filtration, humidity regulation and temperature control are key strategies which can be combined to improve indoor air quality and protect occupants from airborne diseases. Appropriately ventilating spaces with clean outdoor air and minimising recirculation within a building are fundamental ways to reduce the build-up of indoor air pollutants and humidity and decrease the spread of airborne viruses[i]. Recent studies suggest that the SARS-CoV-2 virus spreads more effectively in poorly ventilated indoor environments[v] and that it may be present on the surface of airborne particulate matter[vi]. Research also suggests that for similar viruses such as influenza, an air volume exchange rate of 3 changes per hour, with clean outdoor air, may have the same mitigating effect as vaccinating 50-60% of the population[vii]. In recent years, there has been an uptake of Demand Controlled Ventilation (DCV) systems across building typologies, which minimise the ingress of outdoor air so that less energy is required to maintain a comfortable indoor temperature. As the use of DCV systems encourages the recirculation of air within enclosed spaces, a nexus emerges between energy consumption and its consequent impact on indoor air quality.

The use of passive design strategies to encourage natural ventilation and air distribution—such as building orientation for optimum airflow, appropriately designed openings, effective spatial sequencing and passive stack ventilation—should be prioritised as they require minimal energy input and maintenance over the lifespan of a building. If such measures were to guide architectural decision-making and were tailored to local climatic and site conditions, reliance upon add-on mechanical solutions, such as HVAC systems, could be minimised. In recent years, Computer Aided Design (CAD) tools to simulate natural ventilation and air distribution, both inside a building and its surroundings, have continuously been improving. Developments in Building Information Modelling (BIM), parametric modelling and Computational Fluid Dynamics (CFD), in combination with improved access to fast and inexpensive cloud-based processing, have made airflow simulation tools increasingly accessible to built environment professionals. As these tools have the potential to generate predictive models that can simulate how airborne pollutants and viral particles profligate and spread in a given context, they may also help to bridge the knowledge gap which persists around airborne viral transmission in the built environment. Such models would have far-reaching applications across a range of fields, including building design, where they could be used to inform strategies to optimise natural ventilation and air distribution and mitigate the spread of airborne viruses. However, for models to be calibrated to a useful level of accuracy, they will require additional quantitative experimental data—often constrained by practical challenges such as obtaining affordable and accurate instrumentation which does not add significant heat—and close collaborations between microbiologists, indoor air quality scientists and building flow dynamics specialists.

At sites with high ambient pollution levels, where natural ventilation presents significant challenges, incoming outdoor air can be filtered using appropriately sized High-Efficiency Particulate Air (HEPA) filters to remove viral particles and pollutants, such as $PM_{2.5}$ and NO_2, which are understood to strongly promote COVID-19 transmission[ii]. For most building typologies, designers should avoid relying solely upon mechanical filtration as it requires constant energy input and maintenance demands are often neglected. A number of natural indoor air filtration systems, such as plant- or algae-assisted biofilters, are currently under development, however, more research is needed in terms of their efficacy in removing air pollutants and their effects on relative humidity. While the use of plants to improve indoor air quality has been popularised in recent years, as an isolated measure it is impractical at a building scale, as it requires at least one plant per m^2 to have a substantial impact on indoor air quality[viii].

The specification of non-toxic, breathable and moisture-regulating materials and surface coatings are a low-energy strategy to improve indoor air quality and long-term respiratory health, therefore increasing occupant resilience when confronted with a novel airborne virus. For example, building materials such as lime and unfired clay passively regulate relative humidity (RH) by absorbing and releasing water vapour into the air, therefore reducing the need for mechanical dehumidification. To achieve a healthy indoor humidity level, however, requires a delicate balance. Low relative humidity is thought to favour the survival and transmission of viruses spread via respiratory droplets as it enhances evaporation from exhaled bioaerosols, resulting in smaller droplet nuclei which remain airborne for an extended period[ix]. While, conversely, high relative humidity encourages the growth of indoor mould and mildews, which are linked to an increased risk of asthma and allergies[x]. In addition, the chemical properties of materials can play a key role in slowing the spread of pathogens and prevent cross-contamination between indoor surfaces. As the SARS-CoV-2 virus has been shown to survive longer on certain materials—up to 3 days on plastic and stainless steel[xi]—antimicrobial materials such as copper-alloys, which destroy or prohibit the multiplication of pathogens, should be considered for high contact surfaces, like countertops and door handles. Specifying antimicrobial materials can also reduce the need for cleaning products, a common source of indoor Volatile Organic Compound (VOC) pollution.

Indoor temperature control, both heating and cooling, remains reliant on the burning of fossil fuels which contributes to high ambient urban pollution levels and therefore the sustained transmission of COVID-19[ii]. During the recent coronavirus lockdown in China, it emerged that in cooler cities such as Beijing the drop in ambient air pollution was notably lower compared to warmer Chinese cities, due in part to a reliance on coal-powered heating for homes and the lower natural dispersion of airborne pollution associated with cooler climates. Similarly, there is a significant global energy demand for indoor cooling—the air conditioning unit is now an expected fixture in buildings around the world. However, mechanical air temperature regulation in most climates can be minimised, or eliminated entirely, by integrating passive temperature control strategies into the architectural design process. Strategies that prioritise the introduction of clean outdoor air can also help to prevent the build-up of indoor humidity, pollutants and viral particles. Generally, in hot climates, indoor airflow should be optimised and combined with an appropriate use of thermal mass; while in cooler climates incoming outdoor air can be preheated through passive systems such as solar heaters and transpired solar collectors, or in mechanical ventilation heat recovery (MVHR) systems.

As the enforced lockdowns begin to lift over the coming months, it is unlikely we will suddenly become an outdoor species. Before the COVID-19 pandemic took hold, urban dwellers in industrialized nations spent over 90% of their time indoors, and, according to the WHO, exposure to indoor pollutants contributed to around 4.3 million premature deaths each year. Given the amount of time people spend indoors, and the future likelihood of airborne viral outbreaks, it is important to re-evaluate how both new buildings and our existing building stock can be designed in order to improve indoor air quality. Built environment professionals should take the lead in the selection and implementation of bespoke design strategies tailored to local climatic conditions which require minimal energy inputs and maintenance over the lifespan of a building. Research opportunities have been brought to light in the fields of viral airborne transmission and detection within the built environment; the effect of building materials on indoor air quality; and the application of breathable, non-toxic and moisture-regulating materials at scale.

While the COVID-19 pandemic has highlighted the need to prioritise design strategies which improve indoor air quality, for these approaches to be successful—and to overcome the inertia of powerful industry stakeholders—it is critical that they are supported by targeted policy change across the public health, urban planning and building design sectors. As, according to the WHO, over 90% of the world's population currently live in places that exceed ambient air quality guidelines, to improve indoor air quality will also require decisive leadership at municipal, national and international levels to enhance the quality of the ambient air in our cities.

Biopic

Otis Sloan Brittain and **Hannah Wood** are both architects with a shared research interest in health and the built environment. They are currently managing the design and construction of 110 prototype homes in Tanzania for Ingvartsen Architects, part of a 3-year randomised controlled trial that investigates how housing design impacts family health. Otis also has an interest in how algae can improve indoor air quality and how this research can be applied in the design of building components. Hannah and Otis have previously contributed to research papers for Cities & Health (2019) and Plos-MED (2018). **Prashant Kumar** is a Professor & Chair in Air Quality and Health, founding Director of Global Centre for Clean Air Research (GCARE), at the University of Surrey, UK; and an Adjunct Professor at Trinity College Dublin, Ireland. He researches urban air pollution, its sources, dispersion and exposure assessment; have published >200 journal articles attracting >6650 citations and h-index of 45. He has secured >£6.5M research funding from RCUK & international bodies, serves editorial board of several journals and reviews/advises as a panel member many funding agencies worldwide.

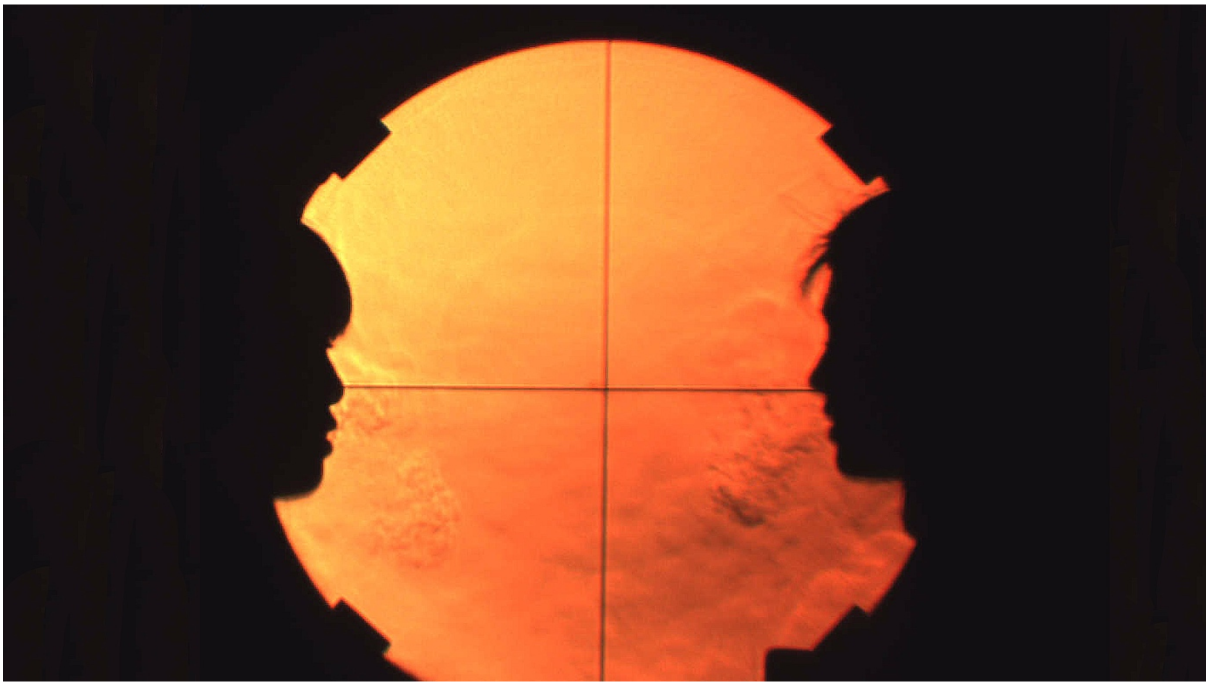

Figure 1. Propagation of exhaled airflow from a pair of subjects face to face talking and breathing. (Image reference: Xu C, et al, (2016). ‘Human exhalation characterization with the aid of schlieren imaging technique’. *Building and Environment,* vol.112, https://doi.org/10.1016/j.buildenv.2016.11.032)

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