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Review

Perspectives on the Sonic Environment and Noise Mitigations during the COVID-19 Pandemic Era

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Abstract: The pandemic has impacted every facet of our life, society, and environment. It has also affected both the requirement and challenges for acoustic research and applications. The present article attempts to present a summary of the impact of COVID-19 on several aspects of acoustics, from the changes in the sonic environment due to reduced human and industrial activities to natural ventilation requirements for mitigating the transmission of coronavirus while mitigating noise, and, more importantly, discusses the potential impacts and challenges for acoustics in the post-COVID-19 era. The present study specifically examines the effects of COVID-19 on the sonic environment, the acoustic treatment by considering the need for constant disinfection, the noise control on construction and neighborhood activities in response to an increased number of people working from home, and the need for having natural ventilation while mitigating noise at home and offices.

Keywords: COVID-19; sonic environment; acoustic treatment; construction noise; natural ventilation

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1. Introduction

On 23 April 2021, *The Times of India*, with the headline "COVID-19: Noise pollution falls as lockdown rings in the sound of silence", reported that for nearly a month, there had been no honking, no whirr of vehicular engines, no echo of loudspeakers, and no clanking of machinery in factories [1]. For nearly a month since the lockdown was imposed, the residents of New Delhi, India, had been waking up to the chirping of birds, which was unimaginable in the pre-COVID-19 period. It was quite a dramatic change from what we knew about the sonic environment of a typical big Indian city. This report was a typical reflection of the reduced noise level in many cities during the COVID-19 lockdown with reduced human and economic activities.

When the World Health Organization (WHO) declared COVID-19 to be a pandemic in early 2020, most countries across the globe shut down their international borders. At the domestic level, outdoor human activities were restricted in order to curb the COVID-19 virus outbreak. Social distancing and self-isolation were effective ways to slow the spread of the virus. In addition, except for a few emergency services, all logistics and transportation facilities were severely disrupted by the pandemic. The report by Eurocontrol [2] on the impact of COVID-19 on European air traffic stated that for the week from 6 to 12 April 2020, immediately after the lockdown, the number of flights decreased by 89.3% compared with the same period in 2019. For the more recent data, the number of flights was 46% from 1–9 June 2021 compared with the same period in 2019. As a result, a significant reduction in environmental noise levels was reported during the COVID-19 pandemic. However, at the same time, other implications included an increased rate of noise complaints by the residents, as most people spent their day at their homes. Furthermore, staying at home over a prolonged period during the lockdown induced higher stress and anxiety levels, affecting the sound perceptions.

The pandemic has impacted every facet of our life, society, and environment, and indeed it will also affect the requirement and challenges for acoustic research and applications.

The recent acoustic-related issues have opened a new window for the acoustician to relook into the current acoustic solutions and amend the changes as per the present scenario.

The present article will attempt to summarize the impact of COVID-19 on acoustics and, more importantly, will discuss the potential acoustic challenges and futuristic solutions for acoustics in the post-COVID-19 era.

2. Impact on the Acoustic Environment during the COVID-19 Lockdown

The unfortunate event of the COVID-19 pandemic has demonstrated a “sound of silence” achieved within a short duration in an unprecedented manner. The reduced human activities and traffic flow during the lockdown have caused drastic changes in the sonic environment. The reported studies mainly focused on the shift in the sonic environment at specific locations due to the lockdown and the emergence of the new sonic environment. Ulloa et al. [3] led a citizen science acoustic sampling across Colombia during the COVID-19 lockdown and measured the impact of human activities in the sonic environment of cities. The sound was recorded during severe mobility restrictions (April 2020) and during a period of tightened restrictions (May–June 2020). They reported a 12% increase in human activities with a significant rise in sound pressure levels of 2.1 dB (a 128% increase). There was a shift towards the dominance of low-frequency broadband signals and a perceived dominance of human-made sounds over wildlife sounds after the restriction. Aletta et al. [4], taking London as a case study, and by taking a series of 30 s binaural recordings at 11 locations representing a cross-section of urban public spaces with varying compositions of sound sources pre-lockdown in Spring 2019 and during lockdown in Spring 2020, reported an average reduction of 5.4 dB (L_{Aeq}). However, they found significant differences in the degree of reduction across the locations, ranging from a 10.7 dB(A) to a 1.2 dB(A) reduction dependent on the urban context. Bonet-Solà et al. [5] analyzed the noise levels in Barcelona, Spain, in eight different locations from January 2020 to June 2020 during the lockdown. Their results in terms of L_{Aeq} showed a drastic reduction of 9 dB(A), especially in nightlife areas of the city, a moderate to high change of 7 dB(A) in commercial and restaurant areas, and a slight decrease in dB(A) in dense traffic areas. Alsina-Pagès et al. [6] analyzed the noise levels in Girona, a 100,000-citizen city in the northeast of Catalonia in Spain, for four different locations from January 2020 to June 2020, including all the stages of the lockdown. The results of the analysis in Girona showed drastic changes in L_{Aeq}, especially in nightlife areas of the city, moderate L_{Aeq} changes in commercial and restaurant areas, and low L_{Aeq} changes in dense traffic areas.

Sakagami [7] presented a study comparing the previously reported results of the acoustic environment in a quiet residential area in Kobe, Japan, under the declaration of the COVID-19 state of emergency in May 2020, with the results of two follow-up studies in the same location in June and July–August 2020, and in September–October 2020. One might expect that the noise during the lockdown period would be the lowest. However, the author found that the noise levels were lower during September–October 2020 than during the emergency declaration in May 2020. From May to October 2020, the noise level was significantly higher in July and August of the same year due to the sound of cicadas that are familiar in this area. He concluded that it was difficult to set the target values of the acoustic environment planning by referring to the low noise level during the lockdown period, as the factor of seasonal changes in the sonic environment would need to be considered.

Munoz et al. [8] investigated the changes in the sonic environment and its perception during the French lockdown period. They acquired data from 21 continuous sound monitoring stations for the entire lockdown period in five conurbations in the south of France. They compared it to typical values in the “normal” situation (before lockdown). A reduction in sound levels of 4 dB to 6 dB was observed from monitoring stations with highly dominant road traffic noise. Mishra et al. [9] investigated the impacts of the COVID-19 lockdown on noise pollution levels before, during, and after the lockdown phase in different residential, commercial, industrial, and silence zones of Kanpur, India. Before lockdown and during the lockdown, the average equivalent noise levels were found to be in the range of 44.8 dB(A) to 79.5 dB(A) and 38.5 dB(A) to 57.8 dB(A), respectively, for different zones. Their results further indicated that the impact of road traffic noise on the risk of high annoyance and sleep disturbance was lower during lockdown compared to that of the pre-lockdown and unlock phase. Rumpler et al. [10] investigated the impact of Sweden's recommendation-based approach of a few imposed restrictions instead of a lockdown through the monitored variation of the city noise levels during the associated period. The data were collected during a campaign of over a full year of noise level measurements at a building façade situated in a busy urban intersection in central Stockholm, Sweden. They found that the recommendations and the restrictions imposed during the ongoing pandemic significantly affected transport and other human-related activities in Stockholm. Basu et al. [11] investigated the sound levels in Dublin, Ireland, before and after the lockdown imposed due to the COVID-19 pandemic. The analysis was performed using measured hourly data from 12 noise monitoring stations between January and May 2020. More than 80% of the stations recorded high sound levels for more than 60% of the time before the lockdown in Dublin. However, a significant reduction in both the hourly average equivalent sound and hourly minimum sound levels was observed at all stations during the lockdown period. This could be attributed to reductions in both road and air traffic movements. Many other reported studies for different parts of the world examined the impact on the sonic environment during their respective lockdown or movement restriction periods [12–19]. A project known as the silent cities project was a participatory monitoring program of an exceptional modification of urban soundscapes during COVID-19 containment [20]. What would be interesting soon is to examine whether the sonic environment will return to the pre-pandemic level when human and economic activities slowly return to normal, keeping in mind that the mode of working may be different after the pandemic, with more people exploring the idea of working from home and the potential of fewer business travels due to the ready availability of cyber meetings compared to the pre-pandemic era. Table 1 summarized the average reduction in sound levels during the lockdown period.

The COVID-19 pandemic has also affected the ecosystem. An article in *National Geographic* [21] reported that the quiet water at Monterey due to the lockdown resulted in scientists better studying the marine world. During the COVID-19 period, all transportations, such as speedboats, yachts, whale-watching tours, and commercial fishing boats, had been barred for tourists. The lockdowns caused by the COVID-19 pandemic enabled several researchers to conduct natural experiments in order to learn how human activities affect animal behaviors [22]. Derryberry et al. [23] found that reducing traffic sound in the San Francisco Bay Area of California to levels not seen for half a century due to the COVID-19 lockdown led to a shift in song frequency in white-crowned sparrows. This shift was especially notable because the frequency of human-produced traffic noise within a certain range interfered with the highest performance and most effective song. Thus, the quiet environment during lockdown allowed the birds to fill the most influential song space quickly. They noticed that the birds responded by producing higher performance songs at lower amplitudes, effectively maximizing communication distance and salience. Tan et al. [24] reported the change in crickets' (and other invertebrates') acoustic properties and exploratory behaviors during the COVID-19 pandemic. Another study revealed that the sudden and dramatic reduction in human activity during the lockdown in the UK led several animals, such as goats and deer, to reclaim Llandudno in Wales and wander the streets of East London, respectively [25].

Most recently, Gibney et al. [26] reported that the COVID-19 lockdown had changed the way Earth moved. A reduction in seismic noise because of changes in human activity was a boon for geoscientists, who indicated that this could allow sensors and detectors to spot more minor earthquakes and boost efforts to monitor volcanic activity and other seismic events.

Moreover, the unprecedented change in acoustic characteristics of the environment during the COVID-19 pandemic has influenced human health. Dutheil et al. [27] hypothesized that, considering the burden of noise exposure in modern society, the COVID-19 pandemic could have the unintended effect of a massive decrease of annoyance and stress related to sound pollution, therefore being a benefit to cardiovascular disease. The American College of Occupational and Environmental Medicine (ACOEM), in an article with the title "Our Relationship with Sound: The Role Noise Plays in Our Lives," stated that people's sense of hearing changed due to the drastic reduction in city noise and the reorganization of the soundscape caused by the COVID-19-related lockdown [28]. Sleep quality was improved because of a substantial decrease in traffic, industrial, and construction noise. They also discovered that they could hear weather changes, birds, and other wildlife from the confines of their homes. The article concluded that one outcome of this newly found tranquility due to the lockdown was that people in cities would undoubtedly become more sensitive to unpleasant noises, especially if they were perceived as unnecessary. Not only will local residents be more sensitive to noise and vibrations, but an increased number of people would continue to work from home as part of their new regular routine, and will therefore be more inclined to report excessive noise levels to relevant government authorities. A sudden rise in construction noise complaints has been reported since the start of the COVID-19 pandemic.

Recently, Díaz et al. [29] presented the potential correlation between noise pollution and the incidence and severity of COVID-19. Their study analyzed the role of short-term noise pollution levels on the incidence and severity of cases of COVID-19 in Madrid from 1 February to 31 May 2020, by using variables including daily noise levels averaged over 14 days, daily incidence rates, average cumulative incidence over 14 days, hospital admissions, Intensive Care Unit (ICU) admissions, and mortality due to COVID-19. Their results showed that noise pollution was an important environmental variable relevant to the incidence and severity of COVID-19 in the Province of Madrid.

A recent study revealed that wearing a facemask altered the speech signal quality; nevertheless, some specific acoustic features remained largely unaffected (e.g., measures of voice quality) irrespective of mask type [30].

Table 1. Summarized data for reduction in average sound levels at various places during the COVID-19 pandemic.

Locations	Average Reductions	Noise Environments	References
Girona, Spain	5 dB (L_{day}, weekend) 11 dB (L_{night}, weekend)	Active areas	Alsina-Pagès et al. [6]
Central Stockholm, Sweden	4 dB(A)	Active areas	Rumpler et al. [10]
Dadar, Mumbai, India	28.5 dB(A), L_{eq}	Indian festival (Ganeshotsav) time	Kalawapudi et al. [13]
Rio de Janeiro, Brazil	10–15 dB(A), L_{eq}	Active areas	Gevú et al. [17]
	3–5 dB(A), L_{eq}	Traffic noise	
Madrid, Spain	3.9 dB (L_{eve}, weekend) 6.3 dB (L_{night}, weekend)	Active areas	Asensio et al. [18]
	3.9 dB (L_{eve}, weekend) 7.4 dB (L_{night}, weekend)	Traffic noise	
Barcelona, Spain	9–12 dB(A)	Active areas *	Ajuntament de Barcelona [31]
	2–6 dB(A)	Heavy traffic highways	
Milan, Italy	7.3 dB(A), L_{den}	Traffic noise	Alsina-Pagès et al. [32]
Rome, Italy	5.2 dB(A), L_{den}		
Paris, France	4.5 dB(A), L_{den}	Traffic noise	Bruitparif [33]

* where human activities are the main contributor, combined with traffic noise.

3. Noise Complaints and Legislation on Noise Control

There is an argument that with less traffic on the roads and some non-essential businesses not operating during the lockdown, other noises might be more noticeable with reduced traffic and environmental noises. Some examples are the noise from garbage collection, construction noise in the neighborhood for essential development projects, and renovation noise from the neighbors. It was reported by *Straits Times* in January 2021 that complaints about noisy neighbors in South Korea spiked amid COVID-19 [34]. Data released by the Korea Environment Corporation earlier in January showed that the number of complaints about noise from upstairs neighbors spiked to 42,250 in 2020, marking a 60.9% increase and drawing concern over the social problems of high-rise living. The leading cause of complaints was stomping on the floor (61%), followed by dragging furniture, hammering, slamming doors, and loud music. Based on a public opinion survey, Dumen et al. [35] reported that despite decreased environmental noise levels during the pandemic, the noise annoyance due to neighbor noise did not change significantly.

Another common complaint was the construction noise. Residents often asked the question as to why the authority was permitting this noisy construction or road work to occur more frequently, especially when most people were expected to stay in their homes. For example, in the province of Ontario, Canada [36], the provincial government sought to provide noise exemptions to essential construction projects to allow for 24/7 construction work for medical facilities and other related services in order to help speed up the response to COVID-19. Tong et al. [37] presented a case study on noise complaints in Greater London, UK. The results revealed that during the COVID-19 lockdown, the number of noise complaints increased by 48%, compared with the same period during Spring 2019. A significant rise in complaints were about the noise sources from construction (36%) and the neighborhood (50%). It has also been reported that the noise complaint categories have changed during the pandemic. In the pre-COVID 19 period, primary noise complaint sources were about the construction and traffic noise, while during the pandemic, most complaints were about the apartment, neighbor, music, daytime constructions, etc. [38]. A recent news report in Singapore [39] also stated that the number of complaints about renovation noise had gone up amid a backlog of projects completed after the circuit breaker (similar to lockdown), plus the fact that more people were working from home because of the COVID-19 pandemic. Table 2 summarizes the recent rise in noise complaints from various places during the COVID-19 pandemic.

Table 2. A summary of rising in noise complaints during COVID-19 pandemic and possible noise sources.

Location	% Rise in Noise Complaints	Noise Sources	References
South Korea	61	Stomping on the floor, dragging furniture, hammering, slamming doors, loud music, etc.	[34]
Province of Ontario, Canada	-	Construction projects	-
London	48	Construction (36%) and neighborhood (50%)	[37]
Dallas, USA	−14 (reduction)	Apartment, neighbor, music, street	[38]
Singapore	-	Renovations, construction projects, neighbor music	[39]

For legislation related to construction, in many countries, the usual legislation is to have a less stringent limit for the construction activities during the daytime when most people are not at home. Construction activities are usually not permitted on Sundays and public holidays when most people are at home. With most people working at home even during the day, there is a question about whether the regulations on construction noise during the daytimes on weekdays should be more stringent. A sudden rise in noise complaints during the COVID-19 pandemic has resulted in amending some changes in existing noise-related regulations. For example, the local council of New South Wales, Australia [40], made a temporary change in existing rules for allowing approved construction sites to operate on weekends and public holidays in order to support the construction industry during this time. Furthermore, the Singapore government had announced in October 2020 an ongoing review of construction noise limits, considering the post-COVID-19 situation in residential areas while ensuring projects would be completed within budget and on time. However, there is no clear answer to this problem. It is a balancing act between a conducive environment for people working at home and sustaining the construction industry, which has suffered badly during the COVID-19 pandemic.

4. Key Acoustic Solutions

4.1. Construction Noise Mitigations

Lee et al. [41] measured the noise profiles of standard construction equipment at their respective noise source. The noise was measured using an acoustic array or acoustic camera instead of using the typical type 1 sound level meters, which would be impossible to isolate the noise profile of a particular machine or process when all the devices were operating at the same time. The study also highlighted the significant presence of low-frequency noise at construction sites for some construction equipment and processes. With working from home to continue during the post-COVID-19 era, there is a need to have noise mitigation measures for construction noise and the use of more low-noise construction equipment. For example, Nakashima et al. [42] reported an ultra-quiet hydraulic excavator incorporating an integrated noise and dust reduction (INDR) cooling system. This excavator could achieve a sound power level that was 5 dB lower than the most stringent restriction level set by the relevant Japanese authority. In addition, Nakada et al. [43] reported buckets with new durable steel laminated dampers, which could reduce noise by five dB(A) from the current level. Another standard solution is the use of a barrier to mitigate the noise emitting from construction sites.

High-rise buildings typically surround construction sites in Singapore, and low-height noise barriers are ineffective for blocking the noise from reaching the higher floors of surrounding buildings. Many investigations of the efficiency of the different obstacles showed that their edge designs would dominate their performance. Karimi and Younesian [44] investigated the performance of T-shape and Y-shape inclined noise barriers in railway noise mitigation. It was revealed that the inclination angle could play a significant role in the noise mitigation level, remarkably in high elevation back regions. Ho et al. [45] carried out experiments in order to investigate the noise reduction by random edge barriers. Their measurement showed that a jagged edge could produce more insertion loss at a high frequency. Ekici and Bougdah [46] presented a review paper on different noise barrier shapes using analytical and physical modeling and full-scale testing. Wang et al. [47] proposed a flat-tip jagged edge profile that was investigated and applied on the edge of a cantilever (slanted up to 45 degrees, facing the noise source) mounted at the top of a passive noise barrier. For future research, one may need to pay particular attention to the potential of a virus attaching to the exposed acoustic foam of the noise barriers facing the construction sites. Acoustic foams are typically exposed to noise for maximum sound absorption. The surface of the foam will need to be either antimicrobial or to be able to service despite frequent disinfection. This problem is similar to the design of acoustic absorbers or acoustic panels with antimicrobial properties in the post-COVID-19 era.

4.2. Need for Noise Barriers with Antimicrobial Characteristics

Many offices were closed, and employees worked from home during the lockdown of the COVID-19 pandemic, conducting much of their business in virtual meetings using tools such as Zoom, WebEx, and MSTeams. Many people have found these virtual communication tools to be effective and more efficient than face-to-face meetings. With an improved pandemic situation, some people might go back to the office, but working from home will be a choice for some professions, and some people's work arrangement could be a mix of working in the office and working from range. In a report by Mckinsey & Company [48] entitled "the future of work after covid-19", by analyzing the potential across more than 2000 tasks used in some 800 occupations in the eight focus countries, and considering only remote work that could be done without a loss of productivity, it was reported that approximately 20 to 25 percent of the workforces in advanced economies could work from home between three and five days a week. The fewer people working in the office would change the existing office's acoustic characteristics and the design for new offices.

Under such circumstances, better speech privacy during the meeting might be required for open offices and the designated meeting rooms. In addition, the use of acoustic absorbers and diffusers, which could be easily washable or disinfected and even possess antimicrobial properties, would be desirable, as the requirement for hygiene would be elevated in the post-COVID-19 era. Besides the acoustic absorbing properties, this added requirement is deemed new for the design and fabrication of acoustic absorbers and diffusers. In a recent study, Sakagami and Okuzono [49] reported the use of a sound absorption technique based on three-dimensional (3D) space sound absorbers in order to solve acoustic deficiency due to the lack of acoustic absorption. They argued that this deficiency would likely happen due to the reduced number of audience members or users of the space due to social distancing. The suggested acoustic absorbers catering to hygiene considerations were microperforated panels (MPPs) and permeable membranes (PMs), which could be easily washable and sanitized. An MPP consists of a thin flat plate made from several different materials with small holes. Several modifications and enhancements to the original design of MPPs by modifying the holes or the back-cavity shape and sizes following the original idea were reported. The MPP cavity will need to be detachable if it is to be washable, as viruses could still enter the tiny holes. Doremalen et al. [50] reported that COVID-19 could persist on surfaces for days. The surface properties of the commonly used acoustic absorbers and diffusers would need to be closely examined because of this concern.

Furthermore, companies that provide acoustic absorbers and acoustic curtains in the hospital environment could be in greater demand, even for everyday workplaces. However, these curtains could be at a higher risk of becoming contaminated with pathogenic bacteria. Hence, it should possess specific properties, such as being bacterial-repellent, hydrophobic, fire-retardant, washable, light-in-weight, and contamination-proof from healthcare-associated pathogens. Recently, Ohl et al. [51] performed a longitudinal study in order to assess the bacterial contamination's period and persistence on several hospital privacy curtains. Al-Tawfiq et al. [52] experimented with the antibacterial characteristics of a privacy curtain made of non-woven polypropylene materials with a special surface treatment. Shek et al. [53] performed an observational study in order to determine the contamination rate of hospital privacy curtains. It was revealed that most of the curtains remained contaminated with bacteria even after fourteen days of their use. In such a pathogenic COVID-19 pandemic, the demand for antimicrobial fabrics has increased. Several traditional curtain materials, such as textiles, including but not limited to polyester, polyester–vinyl composites, vinyl, and even acrylics, possess antimicrobial characteristics up to a certain extent. The effectiveness of an antimicrobial fabric lies in its ability to fend off microorganisms and its ability to help prolong the life of a textile. Chatterjee et al. [54] showed that a droplet would remain as a liquid for a much shorter time on a porous surface, making it less favorable to the survival of the COVID-19 virus. They found that the coronavirus could survive for four days on glass, seven days on plastic, and seven days on stainless steel. However, on paper and cloth, the virus stayed for only three hours and two days, respectively. Hence, a solution could be to use materials with a porous surface that a standard chemical disinfectant could clean. Although the virus may only survive for a few hours, it still poses a risk to the occupants if not disinfected frequently. There is also the possibility of dirt covering the porous surface and thereby altering the surface properties.

On the other hand, the report also reiterated the need for disinfecting glass, plastic, and metal surfaces. Some traditional porous materials may not have antimicrobial properties or could be quickly disinfected by the standard chemical disinfectants or ultraviolet irradiation.

This could be a potential area for future research. Several commercial products have been made from antimicrobial materials that protect all other agents and are cleaned with COVID-19 killing disinfectants. Such products were originally intended for the hospital environment but may be extended to offices, factories, and even households in the post-COVID-19 era.

4.3. Noise Mitigation While Maintaining Natural Ventilation

In the fallout of the COVID-19 pandemic, it has become clear that our reliance on conventional building heating, ventilation, and air conditioning (HVAC) systems needs to be re-thought. WHO has established that enclosed areas with limited ventilation increase the risk of transmission [55]. However, natural ventilation via openings such as windows will allow the noise from the environment, such as traffic and community noise, to enter the rooms. Therefore, a grand challenge is to have a window or open balcony that would mitigate the noise from outside the room or building while allowing for natural ventilation, a panoramic view, and daylight. Several ideas, such as sonic crystals, acoustic balcony, and active noise control techniques, have been reported. Lee et al. [56,57] reported a field experiment of a sonic crystal window that allowed for natural ventilation while enabling a certain degree of natural ventilation in a student hostel at the National University of Singapore. The overall amounts of pink, construction, and environmental noises attenuated by the sonic crystal window were found to be approximately 4.8, 5.0, and 3.4 dB(A), respectively. The typical plenum window was incorporated with sonic crystals [58,59] and a thin perforated box [60] for indoor noise control. Cheung et al. [61] presented specially designed baffle-type windows and balconies for enhancing noise mitigation. The baffle-type window or plenum window consisted of two layers of glass panels. The outer layer provided the opening for natural ventilation.

In contrast, the inner layer was a sliding panel without a direct flow path to the external opening in order to shield the noise. A similar idea could also be applied to the acoustic balcony. This idea was similar to the typical plenum window with an air gap having two offset glass panels [62]. A variation of the plenum window was the supply air window [63]. Bhamjee et al. [64] presented the experimentally validated mathematical and computational fluid dynamics model of a supply air window. The supply air window was an airflow window with multiple panes in which air was pulled in from outside and was heated through conduction, convection, and radiation in the cavity. The environmental noise could also be reduced while saving energy in heating the cold air from outside.

Kim and Lee [65] presented a design known as the air-transparent soundproof window. It consisted of a three-dimensional array of strong diffraction-type resonators with many holes centered on each resonator. Another approach was to incorporate active noise control while enabling natural ventilation. Tang et al. [66] implemented the idea of active noise control into their earlier design of plenum windows. Lam et al. [67] explored active noise control (ANC) as a potential solution for controlling noise that is propagated through an open window. The primary motivation of this technique was to provide acoustic insulation via active means while preserving the natural ventilation properties of the open window. In their more recent work, Lam et al. (2020) described an active sound control system fitted onto the opening of the domestic window that attenuated the incident sound, achieving a global reduction in the room interior while maintaining natural ventilation. Kumar and Lee [68] presented an overview of the fundamental concept of active metamaterials, describing the multiple tuning mechanisms and design strategies and highlighting their potential applications. Lee et al. [69] presented a review of the application of active noise control technologies on windows, focusing on the challenges and limitations. Many reported works focused on the possibility of noise mitigation while maintaining natural ventilation, even before the current COVID-19 pandemic [70–72]. Figure 1 shows the potential designs of the ventilated noise barriers. There may not be too many options for research in this field. The addition of filters for the removal of the pathogen will reduce the natural ventilation.

There may be a reason to relook at louver windows instead of the more popular sliding or casement windows. Based on the frontal area of a window opening, the louver window has the highest percentage of area opening to air breeze. For a typical double track sliding window, the area opening to air breeze is only 50%. Casement windows also have a high percentage of area opening to air breeze by redirecting the air breeze through the window. If the air or wind breeze happens to hit against the glass panel, which blocks its flow through the opening, the air breeze travelling through the gap could be lower. Lee et al. [73] reported that the louver window could attenuate 1.4%, 5.5% and 12.0% of the noise when the panels were partially and fully closed at 30°, 60°, and 90°, respectively, based on experimental measurements. For frequencies below 3000 Hz, the best attenuation occurred around 1700 Hz to 2000 Hz for all panel angles. The mass flow rate was reduced for air passing through the louver window when the panels were partially closed at 30° and 60°, at a reduced rate of 7.7% and 46.2%, respectively, based on computational fluid dynamics simulations. Louver windows could also be used as a passive cooling device. The aluminum slats could be replaced by antimicrobial materials such as copper in the post-COVID-19 era. There is an increased interest in using copper or copper-based composites due to their ability to destroy genomic and plasmid DNA4 [74] and their longstanding antimicrobial efficacy against pathogens such as antibiotic-resistant superbugs [75,76]. Another potential is the use of antimicrobial translucent or transparent coating on the glass panel or the addition of antimicrobial elements into the glass panels.

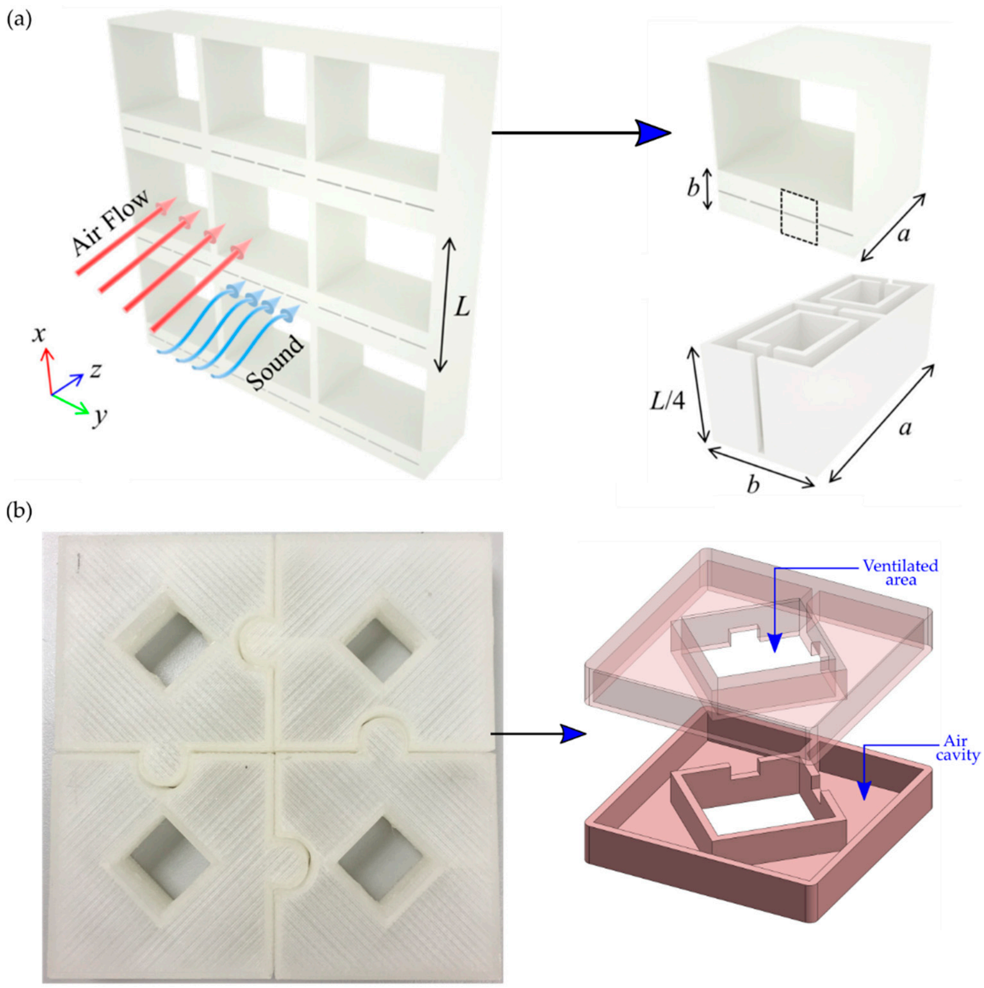

Figure 1. *Cont.*

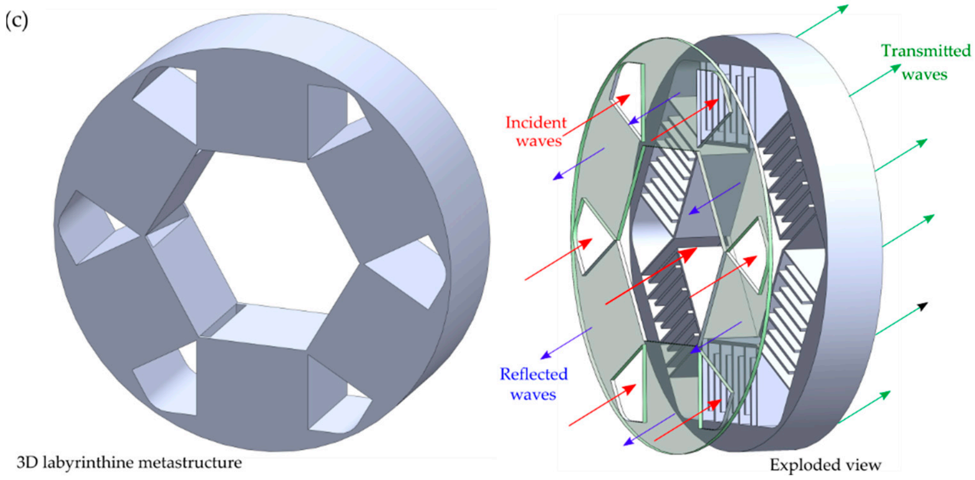

Figure 1. Potential designs for noise barriers with the air ventilation system: (**a**) perspective schematic of the ventilated metamaterial absorbers units arranged in a rectangular lattice. Reproduced with permission from Xiang et al. [77], *Ultra-open ventilated metamaterial absorbers for sound-silencing applications in environment with free air flows*; published by *Extrem. Mech. Lett.*, © 2020 Elsevier Ltd.; (**b**) ventilated window panels. Reproduced with permission from Kumar et al. [70], *Ventilated acoustic metamaterial window panels for simultaneous noise shielding and air circulation.*; published by *Appl. Acoust.*, ©2020 Elsevier Ltd.; (**c**) ventilated labyrinthine acoustic metamaterial unit cell. Reproduced with permission from Kumar et al. [71], *Labyrinthine acoustic metastructures enabling broadband sound absorption and ventilation*; published by *Appl. Phys. Lett.*, ©2020 AIP Publishing LLC. Each design structure is comprised of a sound absorption system and provision for allowing fluid flows, such as air or water, unrestricted passing through the sample.

5. Future Perspective

The COVID-19 pandemic has disturbed every aspect of livelihood on Earth. Several sectors, such as travel, economic activities, research activities, lifestyles, etc., have been significantly affected by the pandemic. It may take a while to bring these activities back to normal, similar to the pre-pandemic era. Few things might change forever. Some acoustic research areas could see a noticeable transformation, as per the post-pandemic requirements to adopt these changes. For example, in terms of businesses, not only will the pandemic change the demand for office space with more people working from home, but it will also change the design of offices and factories in the post-COVID-19 era. The traditional acoustic treatment and acoustic absorbing materials may not meet the new hygiene requirement against virus transmission. In addition, there could be new requirements due to the changing of the office and staff layout in order to implement safe distancing and virtual platforms for cyber meetings. For example, when a new café located at the canteen of the Faculty of Engineering, National University of Singapore, was opened for operation in February 2021 amid the COVID-19 pandemic, patrons and students found the background noise of the café to be higher than expected. The café has an extensive use of glass panels and plastic chairs without curtains, sound diffusers, or absorbers, which could be the reason for the unfavorable reverberation time. The acoustic solutions in the post-COVID-19 era for solving this problem go beyond acoustic curtains, cloth cover for chairs, or acoustic wall diffusers and will differ from past practices. This particular incidence is the impetus for examining the impact of COVID-19 on acoustics.

This current ongoing COVID-19 pandemic has compelled the professionals to consider the new possible design changes during new building construction. Three design strategies, namely, safety, resilience, and sustainability, must be considered for different types of building constructions. As pandemic transmissions can be airborne, waterborne, or through contact, the indoor environment is critical to pandemic control. Hence, the new construction measures should be well equipped to sustain against any potential disaster in the future.

For example, the materials for traditionally used noise barriers, such as curtains, micro-perforated panels, partition walls, etc., should be modified as per the requirements for infection control. Other system design changes, such as ventilation systems, electrical systems, plumbing, and sanitary systems, should be re-structured in order to minimize the virus spread.

6. Conclusions

The pandemic has impacted every facet of our life, society, environment, and it will also undoubtedly affect the requirement and challenges for acoustic research and applications. The main conclusions are summarized as follows.

The reduction in human and economic activities has drastically reduced the environmental noise and transportation noise from vehicles and airplanes. There are positive effects on both human health and animals. However, a significant increase in the noise complaint rates has been reported during the COVID-19 pandemic.

Furthermore, the environmental noise level is likely to be increased with increased economic activities and more people returning to work. Acoustic solutions in the post-COVID-19 era will need to incorporate both antimicrobial properties and the need for frequent disinfection for the design and fabrication of acoustic absorbers, diffusers, fabrics, or curtains. With the increased use of teleconferencing in the office and the requirement of safe distancing, room acoustics will need to pay particular attention to the design of such a space.

With more people working at home, there may be a need to re-examine the current legislation on construction and community noise, especially during office hours. In addition, there will be more complaints about such noise nuisances when people work at home. Moreover, natural ventilation is desirable in order to mitigate the spread of coronavirus. However, noise can also come in with natural ventilation via the window openings. Therefore, there is the need for a more innovative solution for mitigating noise while maintaining a certain level of natural ventilation.

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