ACOUSTICAL, PSYCHOACOUSTICAL, AND PEDAGOGICAL CONSIDERATIONS FOR CHORAL SINGING WITH COVID-19 HEALTH MEASURES

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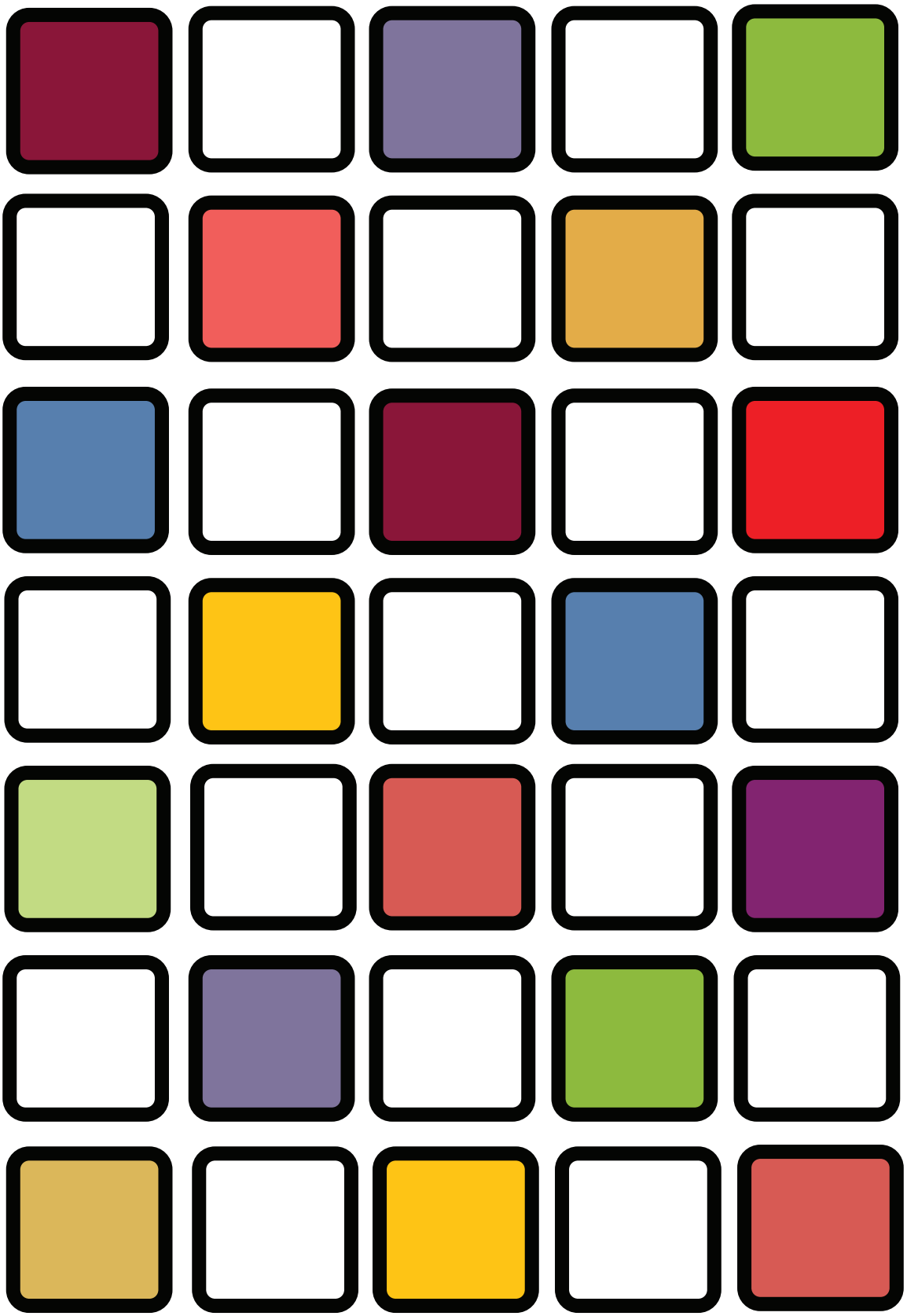
The COVID-19 pandemic has had a tremendous impact on many aspects of daily life. Accepted means for safely gathering persons for any activity include meeting outdoors if possible, maintaining 2 or more meters (6 feet) physical distance between persons, using high ventilation rates (preferably natural ventilation) to provide multiple air changes per hour if indoors, and wearing masks to prevent the spread of larger droplets.[1, 2, 3] However, applying these health practices to choral singing[4, 5, 6, 7] has significant implications for the nature of the sound a choir creates, the perception of the choir's sound both within and outside of the choir, and the vocal production of the singers. In this article, we hope to examine a few of these implications in more detail and to provide some suggestions for how best to respond, based on prior research in the acoustics and psychoacoustics of choral singing, stressing as always that observing necessary health measures is paramount.



Singing Outdoors

Singing outdoors has the potential to remove much if not all of the typical reverberant character of a performance space on the choir's sound (as experienced inside and outside of the choir), radically changing the Self to Other Ratio (SOR) experienced by the singers. By the 'Self' signal, we mean those sounds of one's own voice that arrive directly to one's own ears. By the 'Other' signal, we mean the sum of all *other* sounds that reach the singer, both direct and reflected. The Self-to-Other ratio is represented as the level difference $L_{Self} - L_{Other}$, in dB.[8] A significant component of Other is the diffuse field of sound reverberating in the room. When singing indoors but with wide spacing, the diffuse field dominates the Other sound. When singing outdoors, however, the diffuse field is absent, and only the direct sound from the rest of the voices in the choir remains in the Other. Together with the inverse square law, which states that every time the distance from a sound source is doubled, the intensity reduces by a factor of four,[9] this means that one will hear an Other sound that is weaker and greatly dominated by one's immediate neighbors in the choir, while the singers who are furthest away might be basically inaudible. This has significant implications for maintaining synchronization within the choir.

To help clarify this idea of the effect of the room on the singer and the listener, consider the situation diagrammed in Figures 1 and 2. In Figure 1, the left portion

Figure 1. Room with Reflecting Walls and Ceiling with an Echogram of Sound Energy over Time

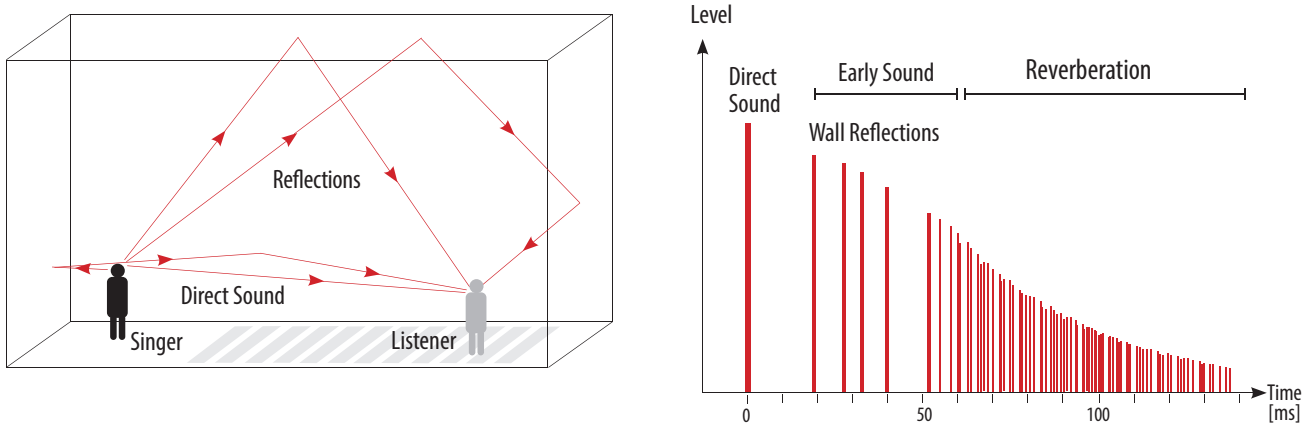
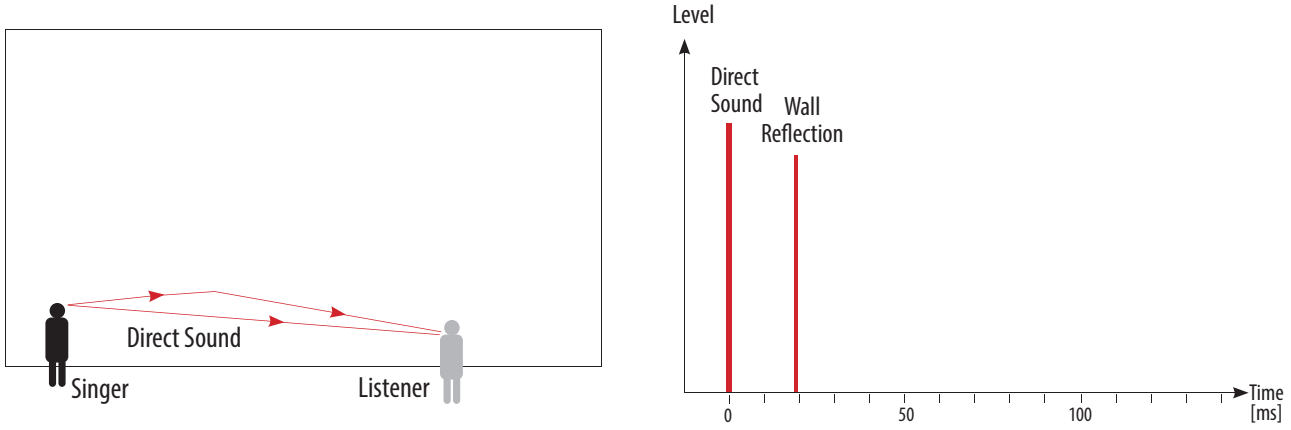


Figure 2. Reflections Outdoors Near a Wall with an Echogram of Sound Energy over Time



represents the typical situation where a singer or singers perform in a room. The singer hears their own direct sound, receives early reflections from nearby walls and perhaps the floor, and gets later reflections from walls and the ceiling, which are further away. The listener gets the direct sound from the singer as well as a vast number of reflections that gradually taper off in strength over time. This gradually tapering reverberation over time is shown graphically on the right. Contrast that with the situation in Figure 2, where the singer and listener are outdoors near a single wall. As there is only one surface for sound to reflect from, the singer receives very little external feedback beyond an early reflection from the wall, and the listener receives only the direct sound from the singer plus one reflection. The effect of the room and its reverberation "tail" is gone, as is shown graphically on the right.

Another aspect of singing outdoors to be considered is the absorption of sound by natural materials. While singers and conductors in a hall have the benefit of reflective and absorptive materials that have been selected and strategically located by building engineers to enhance some aspects of ensembles' sound and attenuate others, outdoors one finds materials that are less regular in shape and location and quite variable in the amount of sound they absorb. This absorption also varies widely with frequency, as can be seen in Table 1. Across the top right of the table, different frequencies one octave apart are shown, with the approximate musical pitch perceived immediately below (with middle C=C4). The numbers below the pitches indicate the ratio of sound absorbed versus sound reflected by each type of material at each octave frequency band, so the lower the number, the less sound the substance absorbs. A concrete floor absorbs only 1 to 2 percent across a wide range of frequencies, so its absorption is very uniform. In contrast, plywood (as might be found in the ceiling of a barn-like hall with open sides) absorbs more at lower frequencies than it does at higher frequencies. Grass, gravel, soil, and indoor/outdoor carpet are modestly absorptive at low frequencies, but become very absorbent at higher frequencies. In such a setting, vowels might be fairly distinct, but high frequency consonants such as /f/, /s/, and /t/would be greatly affected. The SOR also increases as room or space absorption increases, so singers (particularly treble voices) rehearsing or performing on a grass-covered lawn would hear themselves very strongly and relatively little of their colleagues.[10]

Physical Distancing

Increased spacing between singers increases the SOR, whether indoors or outdoors, and tends to make the bulk of the Other sound consist of the direct sound from each choir member's immediate neighbors. With increased spacing indoors, the number of singers on a set of risers

Table 1. Sound Absorption Data of Common Outdoor Materials and Surfaces (from http://mapleintegration.com/sound_ab.php, accessed 7-2-2020)

Material	Frequency in Hertz	125	250	500	1000	2000	4000
	Approximate musical pitch	B2	B3	B4	B5	B6	B7
concrete floor, smooth		0.01	0.01	0.02	0.02	0.02	0.02
indoor-outdoor carpet		0.01	0.05	0.10	0.20	0.45	0.65
plywood 3/8 of an inch thick		0.28	0.22	0.17	0.09	0.10	0.11
loose and moist gravel		0.25	0.60	0.65	0.70	0.75	0.80
grass, 2 inches high		0.11	0.25	0.60	0.69	0.92	0.99
rough soil		0.15	0.25	0.40	0.55	0.60	0.60

or on a stage will by necessity need to decrease. From a viral risk reduction standpoint, fewer singers performing at one time is beneficial, although from a perceptual standpoint for the singers, directors should understand that the SOR will increase as the level of the Other sound is reduced. Increasing the distance between choir members also introduces greater delays in the sound of one performer reaching another.

For a choir used to rehearsing and performing in closer spacing, singing with 2 or 2.5 meters (6.5 to 8 feet) between singers, as an ongoing study in Germany recommends,[11] could result in challenging ensemble difficulties. A 15-meter (49 feet) separation between singers on the edges of the choir on a large stage would lead to a 45-millisecond delay in the sound from one side reaching singers on the other side. Other considerations include sound delays due to the location of accompanying instruments (also distanced from each other, the audience, and from the singers for safety purposes); the location of the singers relative to the audience (again, for safety reasons); changes in the reverberation characteristics of a performance hall with reduced numbers of listeners who are widely spaced from each other (fewer people in the room would tend to make the room more reverberant); and the very real difficulty of the performers seeing the conductor's cues at an increased distance.

Singing Indoors with Increased Ventilation

If it is necessary for the choir to sing indoors, health guidance suggests increasing the room ventilation, preferably with natural ventilation from the outside.[12] Increased ventilation, however, comes with its own set of complications to consider. If flow rates in HVAC systems are increased, the potential for turbulent sounds in the air supply to and air return from the rehearsal or performance hall also increases, which could have an impact on the intelligibility of the sung text. Turbulent sounds in duct systems range in frequency from 31.5 Hz up to 1000Hz—e.g., the full range of the human voice—while noises from airflow around and through the dampers that regulate the amount of air flow and the diffusers that distribute the air evenly in the room range in the 1000-4000 Hz bands,[13] which coincides with the second resonances of many vowels and the frequency of voiced consonants. Furthermore, the well-known Lombard effect, where speakers or singers increase their vocal output in response to background noise, has recently been shown to be sensitive to the specific frequencies of the competing noise and is not merely a general response to overall noise.[14] Thus, one would expect that choir singers would respond to increased room noise in these bands associated with vowel and consonant production and comprehension with increased vocal effort. Increased ventilation, whether natural or through HVAC systems, may also have a drying effect that can impact the ease of the performers' vocal production.

Wearing Masks

Wearing masks that cover the nose and mouth are strongly recommended by the American Centers for Disease Control and Prevention during the COVID-19 pandemic: "CDC recommends that people wear cloth face coverings in public settings and when around people who don't live in your household, especially when other social distancing measures are difficult to maintain."[15] Singing together in a choral rehearsal or performance certainly meets all of the criteria listed by the CDC as a situation where mask usage is warranted, although like the other health risk reduction measures previously discussed in the article, wearing a mask while singing does pose some challenges of which singers and directors should be aware.

One obvious concern is maintaining appropriate coverage of the nose and mouth while still allowing freedom of movement for articulation, especially when opening the mouth wide. This would most importantly apply to the higher range of female singers. From an acoustical standpoint, wearing a cloth or surgical mask while speaking (and, by inference, singing) tends to reduce the intensity of higher frequency components of a voice, especially above 2000 Hz.[16, 17, 18, 19] The perceptual effect of this would be a more dull vocal quality. How singers might respond to this loss of intensity of higher frequency aspects of their voices due to a mask is unknown. The authors surmise that singers might compensate by wanting to sing louder or sharper on the pitch or by making vocal tract adjustments

to "brighten" their timbre. Furthermore, in an indoor setting, masks would appear to damp the very high frequencies that might be already obscured by turbulent noise from ventilation systems.[20] Finally, the effect of wearing a mask on the directivity of the singing voice has not been explored. As this concept of directivity may be unfamiliar to some readers, a summary of information for choral musicians on the directivity of the voice can be found in "The Impact of Location on the Singing Voice" by Harald Jers in the *Oxford Handbook of Singing*.[21]

Practical Suggestions for Choral Conductors, Music Educators, Choral Singers

So far the authors have tried to explain a few of the ramifications of four important and practical means of reducing COVID-19 health risks while gathering together for singing: singing outdoors, increasing physical distance between choir members, increasing ventilation if singing indoors, and wearing a mask before, during, and after singing. We wish to stress that in every situation, the safety of all the participants in a group singing activity is paramount. *Acoustical, psychoacoustical, and pedagogical concerns are not life threatening; artistic concerns are not life threatening; a COVID-19 infection is.* What follows are some suggestions or best guesses, based on prior research and what evidence we have, which may help conductors, educators, and singers enhance the quality of their singing experience *without compromising safety.*

Outdoors

• Locate near a reflecting surface, such as a smooth brick or concrete wall or a performance stage shell; stand on a smooth hard surface, such as brick, concrete, or wood; or stand underneath the roof of an open air covered pavilion. If possible, try to find a wall-less location that is wide but has a low and hard ceiling and floor, and stand in a half circle. Curiously, some forest locations (especially cultivated pines) with many tall straight trunks offer a surprising amount of pleasant reverberation!

• Use music folders as personal reflectors.

• Use block sectional formation, so singers can balance within sections better.

• Select repertoire carefully, especially with regards to contrapuntal part writing.

• Avoid locations with a noisy environment to reduce competing sound sources, such as a loud stream, river or fountain, street noise, or other city noises.

• Do not encourage the singers to sing too loudly. The overall intensity of the sound is not much affected by a mask, but the level in the high-frequency range is greatly affected, attenuating the treble and giving a muffling effect to the mask-wearing singer and the listener. This spectrum change may possibly give the impression of a lower vocal effort, e.g., maybe *mezzo-forte* instead of *forte.* Singers must be guided to resist the intuitive temptation to compensate for this. Singing louder does not increase intelligibility.

• Placement of the audience in an outdoor performance can be crucial. Listeners should not be "downwind" of the singers for health reasons, but should be located away from other noise sources and spread out more laterally so as to not be too far away from the singers.

Indoors

• Use sectional circumambient (equal spacing between singers in all directions) rather than mixed formations to assist within-voice part balance.

• Use natural ventilation with windows and doors open as much as possible instead of HVAC.

• Consider repertoire for reduced forces due to stage size/auditorium limits with safe spacing.

• In the case of long distances between the conductor and choir singers or rooms with high reverberation, consider amplification of the conductor with a headset

microphone in rehearsals in order to clarify announcements by the conductor to the choir.

• If using fans for ventilation, for a given amount of air flow, a larger blade fan running at a low speed would be quieter than a small fan running at a high speed.

• When the conductor wears a mask, consider using one with a transparent window so that the choir can see mouthed cues.

Reinforced Sound

For ensembles with such resources, using individual microphones and a sufficiently large mixing desk with monitor loudspeakers could be an option that opens up many possibilities. When used correctly, a sound system can counteract not only the reduced sound level outdoors but also the greater delays that come with greater spacing between singers. Artificial reverberation, too, is possible. For organizations and schools that have show choirs, what we are suggesting is judiciously applying that technology and expertise to other ensembles. However, for some choirs this will be an entirely new mode of performance that requires a lot of experimentation and practice time in any given venue, not just a "sound check." Perhaps the pandemic can be an incentive for this kind of work.

• It is very difficult to share microphones between several singers in a balanced way, especially when distancing is mandated. The microphones should be individual, preferably of the wireless, fixed position, head-worn type, since most singers do not have the technique for handling microphones. Prices for such microphone systems (microphone, transmitter pack, and receiver) start at approximately $1500 per octet of singers.[22] A power amplifier and multi-channel mixer would also be needed, with the price of these varying with the wattage of the amplifier and the number of channels, respectively. Prices for a 16-channel mixer start at $450.[23] Hygiene precautions such as disposable wind/pop shields and appropriate cleaning are recommended.

• The monitor loudspeakers (for hearing of Other) should ideally be small and many in number, dispersed around/behind the choir for an even distribution of power. A really flat loudspeaker frequency response is more expensive, but it will significantly reduce the risk of feedback, sound better, save time, and reduce annoyance.

• Separate public address speakers facing the audience might not be needed at all, which is good, since they tend to detract from naturalness.

• Initially, a skilled sound technician in full attendance will be needed, to help balancing and optimizing the intra-ensemble listening. The ends of the choir need help to hear the opposite ends of the choir, so a crossed stereo monitoring setup could be advisable.

Other Technological Possibilities

There are other creative ways to use technology to rehearse in a low-risk, distanced fashion. One recent effort involved singers in cars using wireless microphones, which were connected to a receiver/mixing board system; the director then had the singers in the cars tune their car radios to a specific frequency for the mixed feed of the whole ensemble![24] For others seeking an indoor solution, placing performers in separate rooms, each with a computer, external audio interface, and microphone, and using low latency audio software like SoundJack[25] and a local area network internet connection to connect the various performers may be appealing, especially in urban areas where gathering outdoors may not be an option. See the materials created by Ian Howell at New England Conservatory for more information on this option.[26, 27]

Conclusion

The pandemic is an overwhelming experience for all choral musicians. The depth and breadth of safety issues to take into account as educational, civic, and religious institutions consider how to move forward with corporate vocal music are daunting. Even so, as safety decisions are made, we hope that you will consider some of the strategies we have suggested above.

If nothing else, as you make safety decisions about rehearsal and performance locations, distancing between singers, room ventilation, and masks, you will be better informed regarding how those decisions might impact the sound the singers in your choir may hear as they rehearse and perform, and you will be better able to anticipate questions and have possible solutions available before problems occur. Likewise, we encourage you to closely follow the latest research on healthy singing practices in this journal and in other peer-reviewed voice publications. Finally, as vocalists and choral musicians ourselves, we share your desire to once again gather people together in song. May we find safe, smart ways to continue the choral art form for years to come. CJ

NOTES

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CHORAL RESOURCES FOR THESE TIMES

ACDA is hosting a webpage that is updated daily containing resources that are particularly useful for choral professionals: **Resources for Choral Professionals During the Pandemic.**