The Impact of Urban and Traffic Noise on Birds

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Birds, like humans, have problems with hearing in the presence of urban and traffic noise.

Noise Is a Universal Problem

Who has not had the problem of conversing in a noisy restaurant, near a busy highway, or in a congested city street in a large metropolitan area? Other well-documented adverse consequences of elevated noise levels on humans include masking, hearing loss, stress, physiological and sleep disturbances, changes in feelings of well-being, elevated cholesterol levels, and increased risk of cardiovascular disease-related deaths (e.g., den Boer and Schroten, 2007; World Health Organization, 2011; Münzel et al., 2018). Recent studies show that the increasing anthropogenic contributions to the soundscape have the potential to significantly impact not only communication but also the behavior, health, and well-being of wildlife (e.g., Brooks et al., 2014; Shannon et al., 2015; Murphy, 2017; Slabbekoorn, 2018).

Put another way, changes in the auditory world, the soundscape or auditory scene, clearly have an effect on wildlife as well as on humans (e.g., Brooks et al., 2014; Murphy and King, 2014). These potential effects occur in a wide range of terrestrial and aquatic species, and this has become a topic of increased interest to scientists, environmentalists, and government resource agencies as well as city planners and roadway and construction engineers and investigators (e.g., Shannon et al., 2015; Slabbekoorn, 2018; Slabbekoorn et al., 2018).

Interestingly, among terrestrial animals, birds may be uniquely at risk from increases in anthropogenic noise. This is because most birds are highly vocal and rely on vocalizations to defend their territories, maintain social relationships, and find mates. There are over 10,000 species of birds, and probably half of them, the songbirds, parrots, and hummingbirds, must learn their species-specific vocalizations by hearing those of adults of their own species (Marler and Slabbekoorn, 2004). This widespread characteristic of extensive vocal learning and communication in birds is shared only with humans.

Birds and Noise

This paper focuses on the long-standing concern that urban and traffic noise may be detrimental to wildlife, and especially birds, that rely heavily on acoustic communication. The US Endangered Species Act provides additional, compelling motivation for understanding the effects of traffic and construction noise on federally listed bird species that are in danger of extinction. The effects of urban, construction, or traffic noise are probably of little consequence when the noise adds very little to existing ambient-noise levels. By contrast, when traffic noise does add significantly to background noise levels, such as heavy traffic in quieter suburban and rural areas, this extra noise has the potential to produce a suite of significant short- and long-term sensory, behavioral, and physiological changes in birds. These may include

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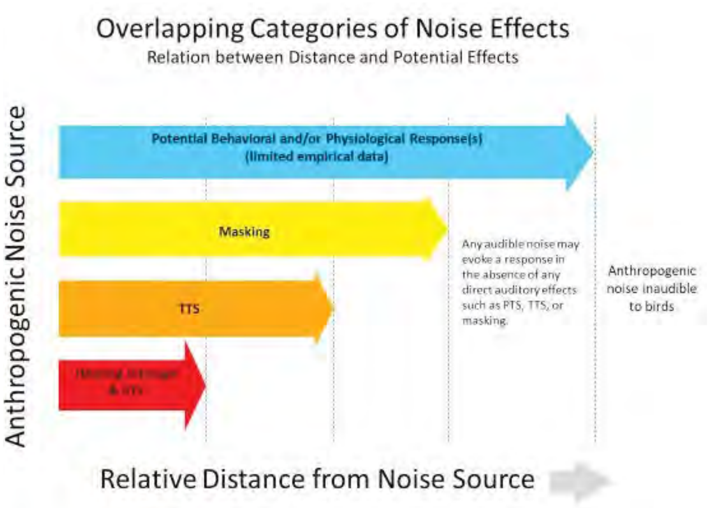

Figure 1. *Conceptual relationship between the distance from the noise source and the overlapping effects of noise on hearing and behavior. When the bird is close to the noise source, all four effects (see text for details) are likely to occur. As the animal moves further away, the effects become systematically less problematic. When the noise source is far enough away, only behavioral and/or physiological effects remain as possible responses to noise. PTS, permanent threshold shift; TTS, temporary threshold shift.*

a decrease in hearing sensitivity; an increase in stress and steroid hormone levels; changes in foraging location and behavior; interference with acoustic communication between conspecifics; and failure to recognize other important biological signals such as the sounds of predators and/or prey. Any of these effects could have long-term consequences and enduring impacts that would come from the concomitant interference with breeding by individuals and populations, thereby threatening the survival of individuals or species.

Noise Can Have Several Effects

Typically, the negative effects of noise are directly related to the level of the noise that usually decreases with the distance of the listener from the noise source. This leads to a simplified scheme for understanding and predicting the complex, overlapping effects of noise that can occur in real world environments (**Figure 1**).

The effects that noise can have include hearing damage and permanent threshold shift (PTS); a temporary threshold shift (TTS) such as when our hearing is temporarily worse after leaving a loud rock concert; masking such as humans experience when conversing in a noisy restaurant; and various other kinds of physiological effects, stress effects, and distraction that we experience from a TV constantly on in the background. All four of these categories of effects could occur simultaneously if the noise exposure was sufficiently intense.

Less intense exposures, or being located further away from the sound source, might eliminate permanent hearing loss from noise exposure, but the other effects such as a TTS, masking, and other behavioral and physiological effects may remain. At an even greater distance from the sound source, the noise eventually becomes barely audible. But even barely audible sounds (e.g., gun shots, fireworks, lawn mowers) might still be capable of causing stress if the human or animal has had previous negative experience with them.

Extensive laboratory data show that birds are much more resistant to hearing loss, auditory damage, and decline in vocal quality from acoustic overexposure than are humans and other mammals (e.g., Ryals et al., 1999; Saunders and Dooling, 2018). This is in part because birds can regenerate the auditory hair cells of the inner ear that are responsible for hearing even after they have been damaged by intense noise exposure. Birds, unlike mammals (including humans; e.g., Lewis et al., 2016), with damaged auditory hair cells subsequently recover a good deal of their hearing and vocal precision when the damaged hair cells are naturally replaced with new hair cells (**Figure 2**; Dooling et al., 2008).

Thus, continuous traffic and urban noise, even if the bird were exposed continuously for extremely long durations (i.e., 72 hours) at extreme levels (i.e., over a 100 dB sound pressure level), is unlikely to cause much of a PTS, hearing loss, or permanent auditory damage in birds, whereas such damage is highly likely in humans and other mammals (e.g., Murphy, 2016). **Figure 2** tracks the changes in the birds' thresholds in the laboratory during and after exposure to 4 different intensity levels of continuous noise for 72 hours. Within a few minutes of exposure, threshold shift is apparent. After about 12-24 hours, threshold shift reaches an asymptote and no further changes in threshold are observed. When the noise stops, hearing begins to recover. Hearing recovers completely within a few weeks for exposure levels of 76, 86, and 96 dB (i.e., it was a TTS) but not for 106 dB, which may have resulted in a PTS of a few decibels, although the birds were not followed for longer than several weeks. Subsequent hair cell regeneration may have resulted in full recovery. There are also species differences in the damaging effects of noise. Canaries and zebra finches recover completely from a 120 dB continuous exposure within a few weeks, whereas budgerigars still have a 10 dB threshold shift several weeks into recovery. A considerable amount is known from such laboratory studies on the growth and recovery of TTS from noise exposure (Ryals et al., 1999; Saunders and Dooling, 2018). Taken together, it is quite clear from these laboratory studies that even in rare instances where birds may remain close to high levels of traffic or urban noise sources for a few hours, it is unlikely to cause permanent hearing loss or auditory damage.

Masking Effects on Communication Can Easily be Underestimated

As the distance from the traffic or anthropogenic noise source increases, the level of the noise exposure usually decreases, and, therefore, birds will have less risk of a TTS from noise. It is tempting to think that there is no risk at these lower noise levels. But there still can be considerable risk if the added noise from traffic is above the natural ambient-noise level. By masking critical sounds, this added noise could seriously interfere with a bird's ability to detect prey, assess its acoustic environment (i.e., auditory scene), and communicate with other birds. Fortunately, there are ways to estimate this risk. Highway engineers can precisely estimate and measure the noise caused by various highways at different distances from the highway. And birds can have their hearing tested in the laboratory, with their thresholds measured precisely in the quiet of an auditory testing booth. **Figure 3** shows a bird's hearing capabilities, displayed as an audiogram, in relation to a typical spectrum of traffic noise.

There is both bad news and good news in **Figure 3**. The bad news for humans is that much of the energy in traffic noise is in the frequency regions important for human speech communication. The good news for birds is that most of the energy in bird vocalizations is at higher frequencies than traffic noise. Still, traffic noise can often include enough energy in the bird's region of best hearing that at close distances, it can have a significant impact on how well birds can hear their species-specific vocalizations.

To return to the noisy restaurant example, the speech from a talker must be at a certain overall level in relation to the overall level of the background sounds produced by other talkers in order to be heard. This is called the signal-to-noise ratio

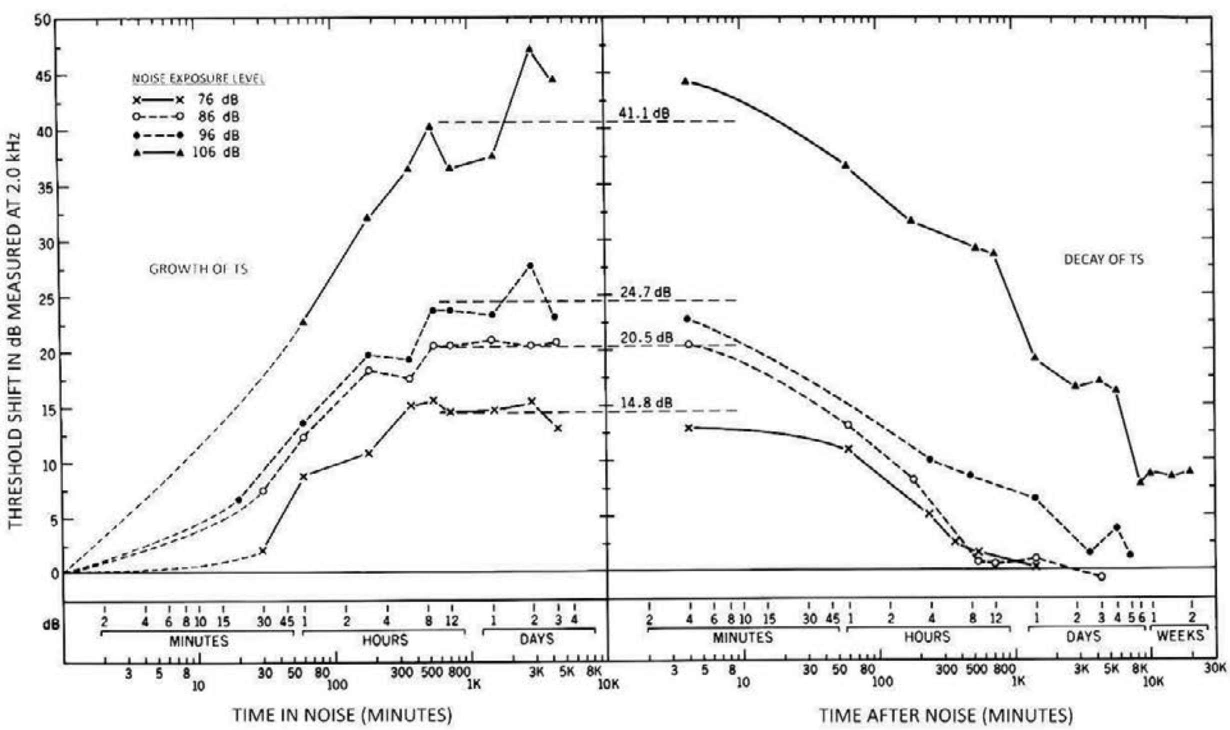

Figure 2. *Growth and decay of threshold shift (TS) from a 72-hour continuous noise exposure in birds. Birds recover their hearing completely within 8 hours for the lowest exposure levels and within 2 days for the 96 dB exposure level. They are left with a 5-10 dB PTS weeks after cessation of exposure to a 106 dB noise.*

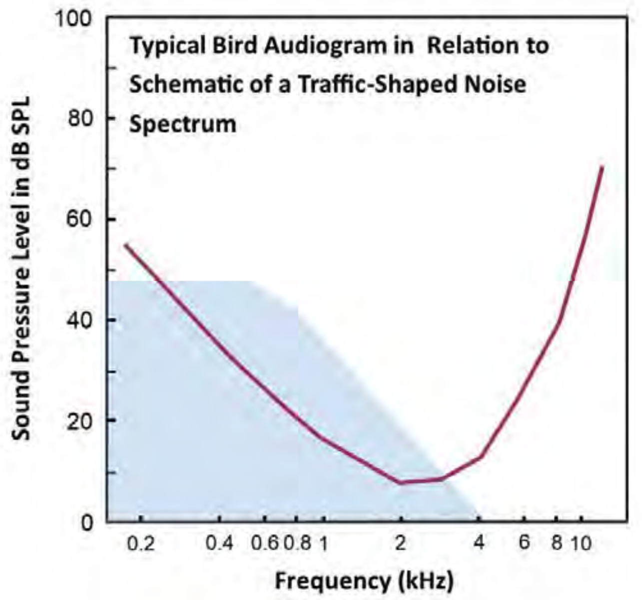

Figure 3. *Typical bird hearing curve (audiogram;* ***solid line****) that shows the lowest sound level an animal can hear at each frequency. From Dooling, 2002. Birds hear best around 1-5 kHz and worse at lower and higher frequencies. Most of the energy in bird vocalizations also falls in this frequency region.* ***Gray area*** *roughly represents the shape of the spectrum of traffic noise, showing that most energy in traffic noise is at lower frequencies and so it will not, at least at low levels, interfere too greatly with birdsong that occurs in the frequency range of best hearing for birds.*

(SNR). There is an extensive literature on humans listening to speech in a noisy environment For humans, the overall SNR at which about 50% of speech may be correctly identified in a steady noise is about −5 dB (i.e., the masking noise is about 5 dB greater in intensity than the speech; Festen and Plomp, 1990). For speech to be heard at a comfortable level that would allow unambiguous acoustic communication and the perception of speech would require a SNR of about 15 dB (Franklin et al., 2006). In a noisy restaurant, for example, the SNR is likely to be, perhaps, around 5 or so dB, adequate for strained conversation but making clear and easy communication impossible.

How masking by noise or other sounds affects hearing has been studied extensively in both humans and birds using simple sounds such as pure tones and white noise (e.g., Dooling et al., 2000). These kinds of masking experiments also provide the best metric for species comparisons. In contrast to the overall noise level referred to above, in these kinds of experiments, the common unit of noise level is called the spectrum level, defined as the intensity level of the noise within a one-hertz-wide band. A comparison of the level of the signal (i.e., a pure tone) and a noise spectrum level also provides a SNR, (measured in decibels) that is used to describe whether a signal has a level above or below the level of the noise and by how much. Either increasing the signal level or lowering the noise spectrum level will allow easier detection of the signal embedded in the noise.

The SNR concept is used to measure an important aspect of the hearing abilities of animals and humans. This "critical ratio" describes an animal's threshold as the SNR of a tone at a level that is just masked by a noise at a fixed level that occurs within a band of frequencies around the signal. Estimates of critical ratios are available for many species including humans and 16 species of birds (Dooling et al., 2000; Dooling and Leek, 2018). Critical ratios derived from pure tones and white noise are the best method of making masking comparisons across species. And the critical ratios have a practical relevance for hearing under natural conditions where ambient or anthropogenic noise might affect the perception of vocal signals and the range over which vocal signals may be heard. They have also been used to study the evolution of detection mechanisms.

Knowing how much noise is effective in masking a signal can, in a more ecological context, aid in understanding which anthropogenic noises may interfere with the acoustic communication of birds in their natural habitats. The data show that the measured threshold for detecting a pure tone is about 20 dB above the spectrum level of the masking noise for humans (i.e. a critical ratio of 20 dB), and it is about 26 dB above the spectrum level of the masking noise for birds (i.e., a critical ratio of 26 dB; Dooling and Leek, 2018).

In other words, humans hear better in noise than birds by 6 dB. It is important to note that signal and noise levels used for calculating the critical ratio are the levels reaching the ear (i.e., measured at the ear of the listener), not at some location distant from the listener. In other words, the same level of noise has more impact on hearing in birds than it does on humans by 6 dB. This 6 dB effect extends over the bird's entire frequency range. Consequently, at 4 kHz, the SNR for detection for humans is about 23 dB and for birds at 4 kHz it is, on average, about 29 dB.

For those interested in determining the extent to which noise might interfere with communication among birds, this 6 dB difference has at least three important implications. First, humans listening to birds communicating in a noisy environment will underestimate the effect of noise on bird communication because humans hear better than birds by 6 dB. Thus, if a human can barely hear a bird singing in the distance, a bird perched on the listener's shoulder will not hear the distant bird at all because the sound has to be 6 dB higher to be detectable by the bird under those same conditions. Put another way, for a point source over a flat reflective surface, sound level decreases by the inverse square law, and a bird would have to close the distance by half (where the sound is 6 dB louder) to hear the singing bird. For a line noise source such as a highway and/or another type of surface, the decrease in sound level with distance can be somewhat greater or less than 6 dB.

The second implication of the 6 dB difference between humans and birds is whether a faint sound off in the distance (e.g., from a construction site) might cause stress in birds. If a human listener can barely hear the distant construction noise, it would be inaudible to birds at the same location as the human listener.

The third very practical implication is that human listeners, without using sophisticated sound-measuring acoustic equipment, can judge the range over which 2 birds might communicate in a noisy environment by using their own ears and applying the simple rule that a 6 dB difference is roughly equivalent to a doubling of distance. In other words, a bird's threshold for detecting a distant bird is about half the distance that it is for a human detecting the same birdsong.

Finally, for a more quantitative estimate, critical ratios measured in birds are a good predictor of how much masking is caused by anthropogenic noises that do not sound like white noise. In fact, critical ratios measured with pure tones and white noises perfectly predict the amount of masking from snowmobile noise and a variety of other anthropogenic noises from man-made sources (Dooling and Blumenrath, 2016).

Different Aspects of Hearing

Consider again the case of listening to speech in a noisy restaurant. It is one thing to detect that someone is speaking in a noisy environment and quite another to be able to understand what is being said. In other words, hearing is obviously more than just detecting a sound 50% of the time in a hearing test, which is the classic definition of threshold and what we measure in a common hearing test.

But if the task is not just to detect whether a sound occurred but to tell whether two sounds are different, the level of the sounds must be 2-3 dB higher than that needed to detect whether a sound occurred. And sounds have to be 2-3 dB higher again to actually recognize a particular sound such as a word. These three aspects of hearing, referred to as the detection, discrimination, and recognition levels of vocal signals, have been measured in the laboratory with a high degree of precision in both birds and humans. These studies have shown that the differences in SNRs required for detection versus discrimination versus recognition are nearly the same in birds and in humans (Dooling et al., 2009; Dooling and Leek, 2018).

As suggested above, we can add still another aspect of hearing in addition to the detection, discrimination, or recognition of a communication signal. The sound for this aspect has a level at which the sound is heard well enough to have comfortable communication. The SNR that represents a comfortable communication level in animals is impossible to assess because there is no way to ask an animal whether it is communicating comfortably. But in humans, the SNR required for comfortable communication is about 15 dB (Franklin et al., 2006; Freyaldenhoven et al., 2006). Because the SNR differences between the hearing levels of detection, discrimination, and recognition are similar for birds and humans, it is possible that a comfortable communication level also exists for birds and that level would be about the same SNR (15 dB) as it is for humans.

If so, then it is reasonable to postulate that there are four different aspects of hearing in birds that are relevant for communication, each of which requires a different SNR (Dooling and Blumenrath, 2016; Dooling and Leek, 2018). For humans, the distinction between these aspects of hearing is intuitive. Field researchers who rely on song playback techniques and monitor the behavioral responses of birds to determine whether a song was heard or not are familiar with a similar phenomenon (Nelson and Marler, 1990). Klump (1996) described this issue as a just-noticeable difference that may be tested in the laboratory versus a just-meaningful difference between stimuli that may be measured in the field.

Working with masking results from the laboratory, it is possible to estimate the theoretical maximum communication distance between two birds using the inverse square law and excess attenuation (i.e., attenuation that occurs as sound travels through a medium like air) for different environments such as open plain versus dense forest (Dooling and Blumenrath, 2016; Dooling and Leek, 2018). These relationships are

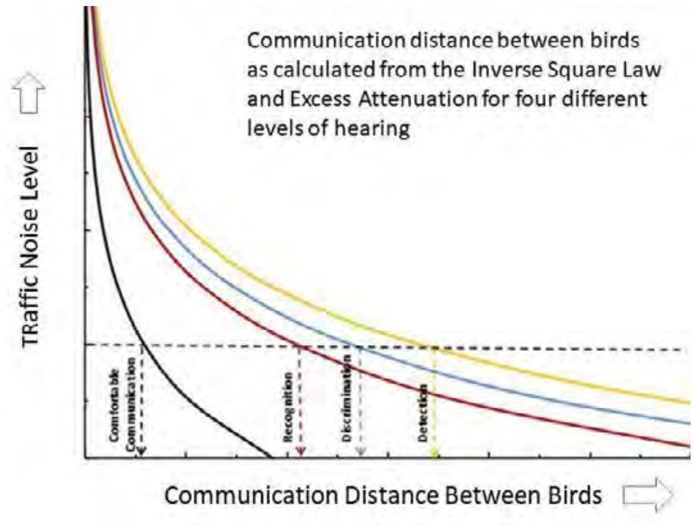

Figure 4. *Effects of anthropogenic noise (in this case, traffic noise) on four different auditory behaviors based on the median bird critical ratio function. In the case illustrated for a hypothetical noise level, the distance between a comfortable communication distance and the distances required for recognition, discrimination, and detection are quite large.*

represented schematically in **Figure 4** showing how the application of these principles provides a view of how well birds can communicate in a noisy environment. The key to making this work is to know, or be able to estimate, the level of the communication signal and the level of the noise at the bird's ear.

The model described above should be useful for establishing quantitative guidelines for the effects of traffic and urban noise on acoustic communication in birds. Again, the required input data are the level of the signal and the noise at the bird's ear. These thresholds also depend on knowing the spectral characteristics of vocalizations, the distance over which conspecific acoustic communication (e.g., the territory size) normally occurs, and the existing levels of ambient noise. Noise levels that limit the maximum communication distances to a distance that is less than the diameter of the bird's territory size (or known communication distances in ambient noise) may have serious biological consequences.

The level of natural ambient noise already present in the bird's environment is a key factor in determining whether additional noise from traffic and other urban activities would have any effect. And variation in territory size, the size of the critical ratio among birds, and natural ambient-noise levels are key variables that make it impossible to use a single noise level as a one-level-fits-all level in terms of estimating whether traffic or urban noise is limiting communication distance by causing additional masking. As noted above, critical ratios have been measured in songbirds and nonsongbirds and there are species differences. These species differences in critical ratios, whether the birds are singing from treetops in relative open areas, down in the canopy of a dense forest, or at ground level where there is ground absorption, are all factors that would affect these distance estimates.

Can Birds Compensate for Noisy Environments?

Returning again to the noisy restaurant example, humans adopt a variety of strategies to hear better in a noisy environment (Roy and Siebein, 2019). From our own experience, these include speaking louder, turning the head, moving closer, changing location, or only vocalizing during pauses in the noise. Like humans, birds also exhibit the Lombard effect, which means that they increase vocalization levels in the presence of background noise (Lane and Tranel, 1971). The Lombard effect has been demonstrated in the field in various bird species (Brumm and Todt, 2002; Brumm and Zollinger, 2011) where it has been shown that birds can raise the level of their vocalizations in response to noise by as much as 10 dB (Manabe et al., 1998).

Both laboratory and field data show that birds use remarkably similar strategies for maximizing communication in noisy environments (California Department of Transportation, 2016; Dooling and Leek, 2018). It is estimated that European blackbirds (*Turdus merula*) and great tits (*Parus major*) could receive an improvement in the SNR equivalent to the benefit from closing the interbird distance in half by simply moving upward about 9 m to a higher perch (Dabelsteen et al., 1993; Blumenrath and Dabelsteen, 2004).

It is also the case that a receiver moving from a lower position to a higher position had a greater impact on whether a vocalization was heard than when the sender moved from a lower position to a higher position. Beyond just detecting a sound, there is every reason to think that the other levels of hearing (i.e., discrimination, recognition, and comfortable communication) would also show similar degrees of enhancements when these various strategies are employed. In a sense then, the distance estimates between communicating birds obtained by applying critical ratios to the problem of two birds communicating in a natural environment represent somewhat of a worst-case scenario. Two birds can utilize a suite of compensatory strategies to enhance the SNR during communication as can humans. Nevertheless, the evidence is clear that noise has negative effects on avian communities, including detection of prey and predators and intraspecies communication. To be fair, there are occasional exceptions to this rule as in the case where noise may interfere with avian predators, making it more difficult for them to prey on birds (Francis et al., 2009).

Communicating in Noise: Bird Communication May be Even More at Risk

We think of speech perception and vocal communication as hearing the structure of individual words and the sequences of words that convey emotion and meaning. As far back as Aristotle (reprinted in 1984), birdsong has fascinated casual observers and, more recently, professional researchers for its similarities to human speech. Over the years, the complex and melodic nature of many species' songs has especially raised interest in the potential parallels between avian vocal sequences and human linguistic patterns.

Recent research aimed at this question has discovered something that is somewhat unexpected. Although birdsong is sequentially complex, birds, in contrast to humans, actually pay less attention to the sequences of elements in their song and much more to the fine acoustic details of each individual element or syllable (Lawson et al., 2018). We now know that birds hear birdsong much differently than humans, focusing on the fine details of each individual element with a much greater resolution than humans (Dooling and Prior, 2017; Prior et al., 2018). This is a level of communication using fine acoustic detail that is beyond human hearing. Thus, it is possible that increases in ambient-noise levels from anthropogenic noises, such as traffic, may have an even more deleterious effect on acoustic communication between birds than we can imagine based on what we know about how noise affects speech communication in humans.

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BioSketches

Robert J. Dooling is professor emeritus in the Department of Psychology and the Neuroscience and Cognitive Science Program at the University of Maryland, College Park (College Park). He received his PhD in physiological psychology from Saint Louis University (St. Louis, MO) while working as a research assistant at the Central Institute for the Deaf in St. Louis. After a postdoctoral fellowship at Rockefeller University (New York), his research has focused on hearing, vocal communication, and vocal learning in songbirds and parrots, with a particular interest in drawing comparisons with similar processes in humans.

David Buehler is managing director and specialist in environmental noise studies at ICF, a global consulting and technology services company. He is a licensed professional civil engineer in California, a licensed professional acoustical engineer in Oregon, and a board-certified member of the Institute of Noise Control Engineering. He has over 35 years of experience and has worked with the California Department of Transportation for over 20 years, conducting noise and vibration studies, developing guidance manuals and training, and managing research studies. In 2005, he was awarded the Federal Highway Administration (FHWA) Environmental Excellence Award for his work on hydroacoustic impact mitigation.

Marjorie R. Leek is a senior research career scientist at the VA Loma Linda Healthcare System (Loma Linda, CA) and professor in the Department of Otolaryngology-Head & Neck Surgery at Loma Linda University Health. She received her PhD in hearing science from the University of Kansas (Lawrence) and completed a postdoctoral fellowship at Boys Town National Research Hospital (Omaha, NE). She has served on the faculty of Arizona State

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Arthur N. Popper is professor emeritus of biology at the University of Maryland, College Park (College Park) and editor of *Acoustics Today*. Although most of his research has been on hearing in aquatic animals, he has collaborated with Robert J. Dooling for many decades on more general issues of hearing, including the effects of anthropogenic sound on various vertebrate taxa. He received his doctorate from the City University of New York and did his research in the Department of Animal Behavior at the American Museum of Natural History (New York). He then was on the faculty of the University of Hawai'i (Honolulu), Georgetown University (Washington, DC), and finally the University of Maryland, College Park.