CONCEPTUAL AND COMPUTATIONAL MODELS OF THE EFFECTS OF ANTHROPOGENIC NOISE ON BIRDS

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1 INTRODUCTION

Highway and other anthropogenic noises can cause a variety of adverse effects on birds and other wildlife. These effects include stress and physiological changes, auditory system damage from acoustic overexposure, and masking of communication and other important biological sounds [1], [2], [3], [4], [5], [6]. A precise understanding of these effects is of interest to many groups including biologists, environmentalists, and government regulators, as well as city planners and roadway and construction engineers. However, for a number of reasons, it is difficult to reach a clear consensus on the causal relationships between noise levels and these adverse effects. One reason is that there are surprisingly few studies in birds that can definitively identify anthropogenic noise alone as the principal source of stress or physiological effects. A second reason is that, while all humans have similar auditory capabilities and sensitivities, the same is not true for birds [17], [18]. Still another issue is separating the various effects of noise. There are well documented adverse consequences of elevated noise on humans including hearing loss, masking, stress, physiological and sleep disturbances, and changes in feelings of well-being, and it would not be too surprising to find a similar range of effects in birds.[7].

A recent review of the effects of highway noise on birds [24] attempted to provide a framework for conceptualizing the separate and integrated effects of anthropogenic noise on birds, particularly those of masking. This is useful because independent of other effects, masking of communication signals and other important biological sounds (e.g., sounds of an approaching predator) can potentially have significant adverse consequences for species' behavior [23] and population viability [25]. Most vocal species rely on acoustic communication for species and individual recognition, mate selection, territorial defense, parent-offspring communication and detection of predators/prey [25]. Understanding how and to what extent masking can affect communication between individuals is an important first step toward determining the level of impact to them, and to the species.

Here we first describe the conceptual model that identifies and differentiates the four classes of anthropogenic noise effects on birds and the spatial relationships among them. We present this model to provide a heuristic baseline for differentiating the four classes of anthropogenic noise effects and to highlight the relative importance of masking. We then present a computational model that shows the effects of masking on communication distances between birds exposed to noise, based on their auditory capabilities and the acoustic dynamics of signal transmission in different environments.

2 FOUR CLASSES OF ANTHROPOGENIC NOISE EFFECTS ON BIRDS

There are generally four overlapping categories of anthropogenic noise effects on birds: hearing damage and permanent threshold shift (PTS) from acoustic overexposure, temporary threshold shift (TTS) from acoustic overexposure, masking of important biological sounds, and other physiological and behavioral responses. In all but the last case, these auditory effects depend strongly on the level of noise exposure which is highly correlated with the proximity of the bird to the noise source. These relations are schematically represented in Figure 1. Highway noise (left margin) is used as an example of an anthropogenic noise source. This figure, adapted from a recent report on the effects of highway noise on birds [24], shows the conceptual relationships among noise level, distance of the bird from the noise source, and the different kinds of effects of noise on birds in order to disintangle these effects from those of masking alone.

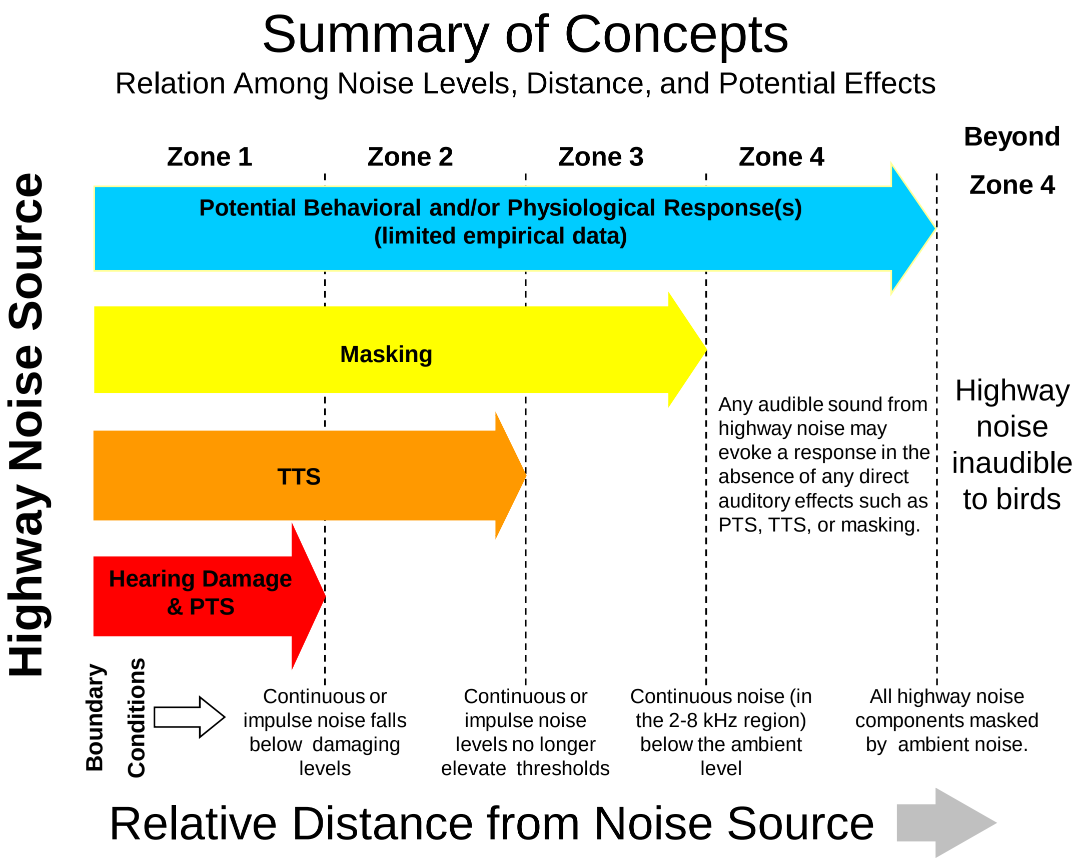

Figure1: Summary of Noise Concepts

2.1.1 Effects Expected in Zone 1

If a bird is in this zone, traffic noise and construction noise can potentially result in hearing loss, threshold shift, masking, and/or other behavioral and/or physiological effects. Laboratory evidence shows that continuous noise levels above 110 dB(A) SPL or a single blast noise over 140 dB SPL (125 dB SPL for multiple blasts) could result in physical damage of the auditory system and permanent threshold shift. These exposure limits are derived from several studies of noise damage in birds and more extensive literature in mammals, including humans [9], [10], [11], [12], [13]. Taken together, birds present an especially interesting situation in terms of acoustic overexposure. Birds are more resistant to both temporary and permanent hearing loss and to hearing damage from acoustic overexposure than are humans and other mammals [6]. Moreover, unlike mammals, birds can regenerate the sensory cells of the inner ear, thereby providing a physiological mechanism for recovering from intense acoustic overexposure [5], [6], [8]. Extrapolating from laboratory studies of acoustic overexposure in birds [9], [10], it is possible to estimate hearing damage that might result from exposure to many common noises such as highway noise and continuous and impulsive-type construction noise.

2.1.2 Effects Expected in Zone 2

At greater distances from the highway, as noise from the highway decreases in level, hearing damage and permanent threshold shift are unlikely to occur. Again, however, laboratory data show that high noise levels above about 93 dB(A) SPL, though they do not cause permanent damage, might still cause a temporary elevation of a bird's hearing threshold, mask important communication signals, and possibly lead to other behavioral and/or physiological effects. [15]

2.1.3 Effects Expected in Zone 3

At even greater distances from the highway the noise levels are even lower. Here, where the spectrum level of the highway noise is still at or above the natural ambient noise level, masking of communication or other biologically important signals can occur beyond that which already occurs from natural ambient noise. As far as we know, the range over which masking effects may occur has not been systematically investigated in the field. But this range can be expected to be quite large in otherwise low noise environments. In noisy environments, as for instance on a windy day, the masking effects of anthropogenic noise will not extend as farfrom the noise source. In either case, the range is bounded at the furthest distance from the noise source where the levels of anthropogenic noise fall below the ambient noise level [19], [22].

2.1.4 Effects Expected in Zone 4

Once the level of highway noise falls below ambient noise levels in the critical frequencies for communication, masking of vocal signals is no longer an issue because the noise can no longer be heard by the receiver. However, faintly heard sounds falling outside the region of bird vocalizations, such as the low rumble of a truck, may still potentially cause other behavioral and/or physiological effects.

2.1.5 Effects Expected Beyond Zone 4

Beyond Zone 4, the energy in traffic noise and construction noise at all frequencies is completely inaudible to the bird (i.e., falls below the bird's masked threshold) and can be expected to have no effects of any kind on the bird.

3 EFFECTS OF MASKING ON COMMUNICATION

The main focus of this paper is to address the masking effects of anthropogenic noise from the point of view of the listening bird. Students of bird hearing have long recognized that there is a strong correlation between the range of hearing in birds and the frequency spectrum of bird vocalizations [16], [17]. Masking is the interference with the detection of one sound by another. Technically, masking refers to the increase in thresholds for detection or discrimination of sounds in the presence of another sound. The simplest kind of masking experiment is to measure the sound detection thresholds for pure tones in the presence of a broadband noise. These signal-to-noise ratios in masking (i.e., critical ratios) are now available for 14 different species of birds [18] so we have a fairly good idea of how the average bird hears in noise.

3.1.1 Masking Effects on Different Aspects of Hearing

Common sense and our own experience tell us that acoustic communication can be severely constrained if background noise is of a sufficient level. Such noise decreases signal-to-noise-ratios and therefore limits the acoustic space (the combination of sound frequencies and levels that are audible) of a sound. Noises can be continuous or intermittent, broadband or narrowband, and predictable or unpredictable in time or space. These noise characteristics determine the strategies that birds might employ to minimize the effect of noise on acoustic communication. Background noise makes it harder for an animal (or human) to detect sounds that may be biologically relevant, to discriminate among these sounds, to recognize these sounds, and to communicate easily. Studies on the effect of noise on hearing in birds and humans show that signal discrimination requires a higher signal-to-noise ratio than detection; recognition requires a higher signal-to-noise ratio than discrimination; and comfortable communication requires an even higher signal-to-noise ratio [19], [20]. Below we use this information to estimate the effect of anthropogenic noise on acoustic communication in birds.

3.1.2 The Significance of Noise Spectrum and Signal Spectrum in Determining Masking Effects

Most laboratory studies estimating the effects of noise on signal detection use continuous noises with precisely defined bandwidths, intensities, and spectral shapes. Traffic noise on heavily traveled roads can approximate these features (e.g., relatively continuous, relatively constant spectrum and intensity). This provides the opportunity to move from laboratory results based on continuous noises to predictions of behaviors in the field (e.g., communication distance) that might be affected by anthropogenic noises such as highway noise. From masking studies in birds, humans, and other animals, it is known that the noise in the frequency region of a signal is the most important acoustic feature in masking the signal--- not noise outside that frequency band. Thus, since typical highway noise has more energy below 1 kHz than above, and bird vocalizations generally contain more energy above 1 kHz than below, the masking effects of highway noise on bird vocalizations are less than would be expected from noise of the same level in the same frequency range of bird vocalizations [19].

3.1.3 Modelling the Effects of Masking by Traffic Noise on Bird Vocal Communication

To evaluate the effect of masking noise on bird communication, we developed a model that integrates the spectrum and level of the masking noise, the bird's hearing in quiet and noise, the spectrum and level of a signaling bird's vocalizations [21], and the acoustic characteristics of the environment. The model assumes that the spectrum and amplitude level of the noise and the signaler's vocalization are both known at the location of the receiver. These values can either be measured directly or they can be estimated by applying signal attenuation algorithms to both the noise source and the signals of the sender. The algorithms adjust the spectra and level of the noise and of the signal transmitted over distance and through different habitats (e.g. meadows, forests) between the communicating birds. The challenge for the receiver is to hear the signal in the presence of noise. This is dependent on the species-specific auditory capabilities of the receiver such as how well it hears in noise (i.e., its critical ratio) and the signal-to-noise ratio at the receiver's location. Using a human parallel, the model also incorporates the notion that different auditory behaviors (e.g., communicating comfortably versus just being able to detect that something was said) require different signal-to-noise ratios.

Figure 2 shows the effect of anthropogenic traffic noise on four different auditory behaviors based on the median bird critical ratio function. The specific case illustrated is for a background noise level at the listening bird of 60 dB(A) – a level typical of traffic noise measured roughly 300 meters from a busy 6 lane highway. This example assumes the calling bird is vocalizing at a peak sound pressure level of 100 dB through an open area and the vocalization is affected by excess attenuation, beyond the loss due to spherical spreading, of 5dB/100 meters. In this noise, a comfortable level of communication between two birds requires a distance between them of less than 60 meters. Recognition of a bird vocalization by the receiver can still occur at greater inter-bird distances up to about 220 meters. Discrimination between two vocalizations is possible at inter-bird distances up to 270 meters. And finally, simple detection of another bird's vocalization can occur at distances up to 345 meters in this noise.

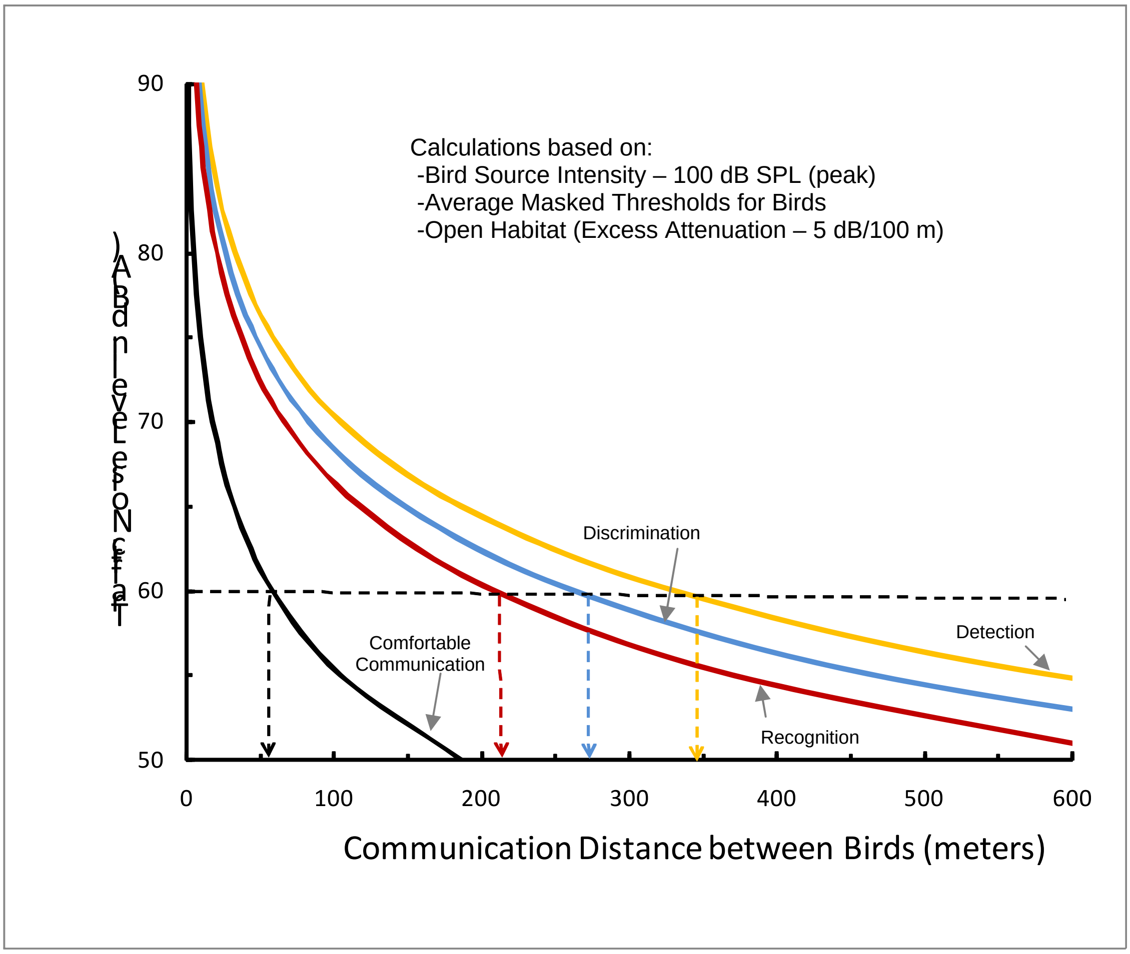

Figure 2: Effect of Traffic Noise on Communication Distance

In Figure 2, the distance values computed for a 60 dB SPL level of traffic noise can be used to construct a receiver-centric map of distances corresponding to the four different auditory communication behaviors. This is schematized below in Figure 3. Communication distance between the sender (along the periphery) and receiver (at the center) is represented as the radius “r” for the concentric circles defining the boundaries of each of the four levels of communication. While any increase in ambient noise level from anthropogenic sources can potentially affect acoustic communication, which auditory behaviors are affected depend on the noise level. In figure 3, the inner circle represents the case where the sender is close to the receiver. This represents a signal-to-noise that is sufficiently large that the sender and receiver can communicate comfortably. As the sender moves away from the receiver, the signal level and therefore signal-to-noise ratio, at the receiver drops. At this distance, the receiver can no longer communicate comfortably but can recognize a sender’s different vocalizations. If the sender moves even further away, the receiver can still discriminate between two vocalizations but cannot reliably recognize them. Finally, at the outer perimeter, the signal level at the receiver results in such a low signal-to-noise ratio that the receiver can just detect that some kind of a sound has occurred. The distance over which masking from anthropogenic noise sources occurs can be quite large. This schematic provides a way of estimating and quantifying the risk to acoustic communication in birds at different distances from a noise source.

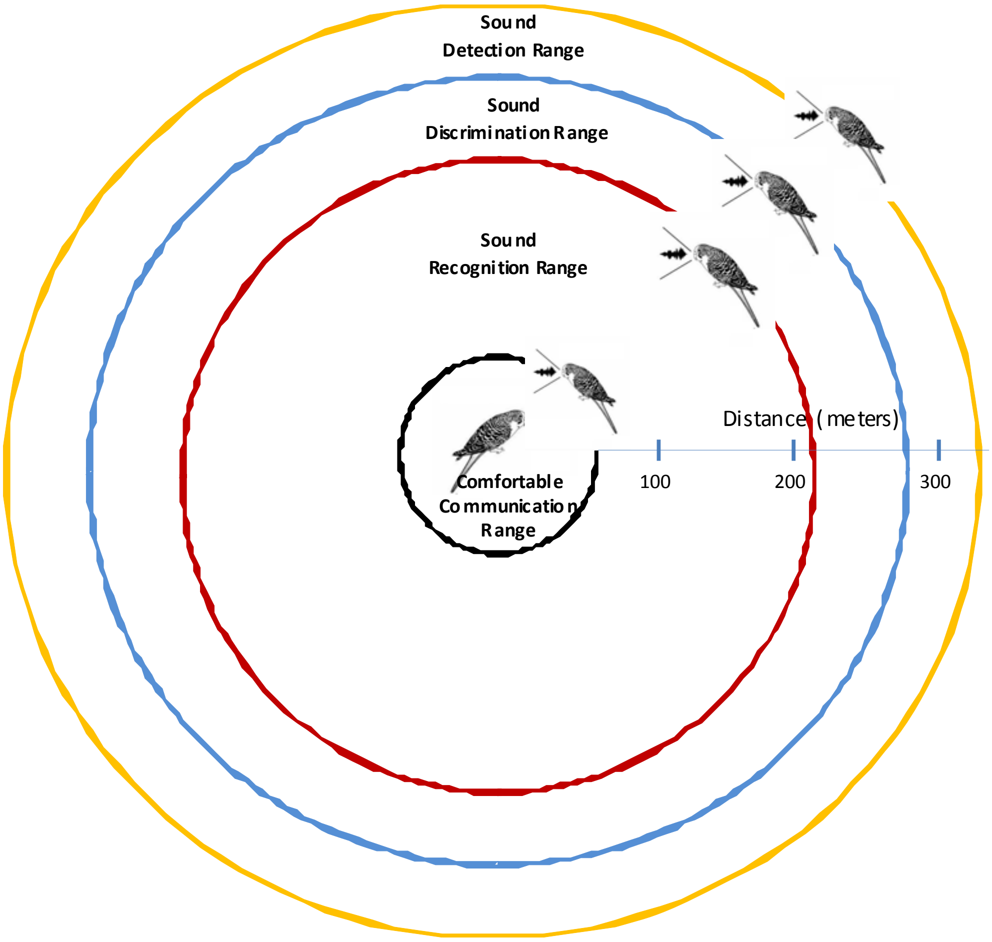

Figure 3: Receiver Hearing Ability by Sender Distance

In real-world situations, the acoustic dynamics of signal transmission are highly variable, both spatially and temporally, depending upon distribution and character of habitat types, prevailing meteorological conditions and the relative behaviors of the caller and receiver. Consequently, the shapes and sizes of the communication regions around the receiver will naturally vary in accordance with the physical conditions of the area, the species-specific hearing capabilities, and the strategies employed in communicating acoustically. Figure 3 shows how proximity to a linear noise source such as a highway would affect communication range in the simplest case of a uniform, open habitat. Communication distances for birds closer to the noise source, or with large critical ratios, would be represented by smaller concentric circles. Communication distances for birds further away from the noise source, or with smaller critical ratios, would be represented by larger concentric circles.

4 DISCUSSION

The impact of anthropogenic noise on communication in wildlife depends on: (1) the level of the noise but also its spectral composition, (2) the level and spectrum of the sender's vocalization at the receiver, and (3) the receiver's species-specific auditory capabilities. Noise within the spectral band of the signal, if it rises above ambient levels, can mask these communication signals thereby degrading or eliminating effective communication between individuals. In nature, the shape of the areas around the receiver demarcating different auditory effects as shown in this model would actually be irregular polygons reflecting habitat-specific differences in excess attenuation (e.g., ground effects and signal scattering in vegetation) as well as the relative locations of the two birds and the receiver's distance from the noise source. It is clear from this illustration that for birds communicating close to a noise source where noise levels are high, the area of the effective communication will be reduced. This approach of considering communication from the standpoint of the receiver may provide a useful metric for evaluating the actual noise impact on individuals, or collectively on populations, in areas subject to anthropogenic noise exceeding ambient levels. For instance, in determining risk to a species, the communication distances derived from this model might be considered in relation to other aspects of biology such as territory size.

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