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ENVIRONMENTAL ACOUSTICS AND CENSUSES OF SINGING BIRDS

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ABSTRACT.—The tasks in a census of singing birds include: (1) identification of the species of a singer, and (2) estimation of the location of the singer. The acoustical properties of the environment interfere with both these tasks; effects depend on the type of habitat. In open fields the primary sources of degradation are attenuation and amplitude fluctuations. Attenuation limits the maximum range of detection, and alters the frequency composition of the sound as heard by the observer. Fluctuations are random, and interfere with amplitude modulation. They may also cause error in estimation of distance. In forests attenuation has a similar effect, though the exact values depend on the type of forest. Reverberation is of major importance as a source of sound degradation, and virtually obliterates the fine details of songs at moderate distances, interfering with recognition. Sound scattered by trunks and foliage also makes estimation of the location of the singer more difficult. Adaptations by birds to combat the effects of song degradation by the environment may both help and hinder species identification and location estimation.

A census of singing birds has three tasks: (a) detection of the presence of a singer, (b) identification of the species of the singer, and (c) estimation of the location of the singer so that a distribution map may be compiled. Many factors, including hearing ability, extraneous noise and the acoustical properties of the environment, affect the performance of human observers on these tasks. The acoustical properties of the environment, which may be unknown to persons who census birds, will degrade bird song in a variety of predictable and unpredictable ways.

The song emitted by a bird is degraded by attenuation, fluctuation, and reverberation, all of which are both frequency and distance dependent, and vary among different habitats. The problem is not simply an increase in the difficulty of detecting a song with distance; a sound may be detectable, but accurate species identification may be difficult owing to degradation of the structure of the song. In addition, with increasing distance, error in estimation of the position of a singer may also increase. This paper will discuss the sources of environmental degradation of bird song, help define favorable acoustic conditions, and suggest empirical studies aimed at minimizing and controlling these effects in censuses.

ATTENUATION

Attenuation, the decrease in the intensity of sound with distance, is influenced by a number of environmental factors. In an ideal free field (with no sources of absorption or scattering), sound will spherically diverge from a point source, and the intensity will decrease by 6 dB with each doubling of distance. In the environment of a bird there are sources of excess attenuation which further reduce the intensity of a sound at a given distance. These include molecular absorption, which varies with humidity and air temperature, absorption and scattering by heterogeneities in the air (eddies), absorption and scattering by soil, and absorption and scattering by foliage. All become more troublesome with higher frequencies. The presence of wind and thermal stratification in the air may also have an effect, sometimes to the extent of creating a sound shadow which results in a sharp attenuation of sound beyond a certain distance.

Attenuation creates several problems, both for birds trying to communicate, and for ornithologists attempting censuses. First, it limits the maximum distance at which a song can be heard. This maximum range depends on the characteristics of the sound at the source and the acoustics of the habitat. Morton (1975), Marten and Marler (1977), Marten et al. (1977), Bowman (1979), and Linskens et al. (1976) have measured attenuation in various habitats. Their measurements do not agree closely, and are probably of little use as an indicator of maximum detection distance of bird song. For that, it is necessary to perform measurements in the habitat in which the census is being carried out. The previous studies do agree that attenuation is frequency dependent, with maximum transmission in the midrange frequencies from 1 to 4 kHz, those frequencies found in most passerine bird songs.

Two important factors affecting attenuation vary even within a given habitat: the time of day and the presence or absence of foliage. Time of day affects wind and thermal stratification, as these are largely dependent on solar heating. In north temperate forests, sudden growth in foliage occurs in the spring (usually in the middle of the census season) and can increase the absorption of higher frequencies. These factors differ in importance in forest and field habitats. Under the canopy of a forest, where little thermal

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stratification develops, change in foliage is likely to have a much greater effect than time of day. In an open field there is a much greater time of day effect, and little effect from growth of foliage.

A more subtle factor, affecting species recognition rather than detection, is the frequency-dependent character of the attentuation. Attenuation greatly increases above the 1–4 kHz mid-range frequencies. Birds with a high-frequency component in the song useful for identification will be more difficult to recognize even if the low-frequency song component has been detected.

FLUCTUATIONS

Random fluctuations in the received level of sound are present owing to microclimatic heterogeneities in the transmission path (air eddies). These are undoubtedly responsible for some of the scatter in measurements of attenuation by various researchers. They are important to censusers for two reasons: they cause variability in detection distances and distance estimates, and they interfere with species identification.

The important parameters of fluctuations are the amplitude and the periodicity. Measurements by Richards and Wiley (1980) indicate that the amplitude of the fluctuations increases with frequency and distance, and is influenced by wind and thermal conditions in the air. The periodicity of the fluctuations determines the type of interference with communication. Long period fluctuations, changes in attenuation with time of day, for example, will affect the distance at which a song can be detected, but will not affect recognition of that song. Fluctuations with periodicities similar to those of amplitude modulations in the song can cause difficulty in species recognition, while having little effect on detection distance. The results of Richards and Wiley (1980) show that fluctuations are most severe at frequencies below 20 Hz, and interfere with amplitude modulation in that range. For this reason amplitude modulation is probably not used for species recognition in most open field species, but is nevertheless characteristic of many species songs. Fluctuations could mislead ornithologists using this characteristic for identification.

Birds have evolved a strategy for minimizing the effects of both attenuation and fluctuations: sing in the early morning hours before the effects of solar heating become important. Ornithologists generally census at this time as well. Though this strategy will maximize detection distance, and minimize the effects of fluctuations on species recognition, it cannot decrease the differential attenuation of the higher frequencies with distance. Observers should be trained not only in recognition of high-quality songs recorded in close proximity to a bird, but also in recognition of songs recorded from a considerable distance, at which the intensity relationships of the various frequency components may be changed.

REVERBERATION

Potentially the most severe problem for song recognition and localization in a forest, one which has been largely neglected in favor of studies of simple attenuation, is reverberation. Reverberation is also the most complex form of acoustic degradation in natural habitats, and is difficult to measure and study.

Scattering and reverberation of sound can result from the presence of trunks, foliage, and ground. The results of Richards and Wiley (1980) show it to be strongly frequency dependent. The effects of distance have not yet been studied. The frequency dependence is due to the relationship between the size of the scatterers and the wavelength of the sound; wavelengths greater than the dimensions of the scatterer are not scattered. Wavelengths approaching the dimensions of the scatterer and smaller are deflected to varying degrees. Since the higher frequencies in bird song have wavelengths comparable to the size of leaves in deciduous forests, they are degraded more severely by reverberation than the lower frequencies.

Scattering of sound in the path of the beam will have the initial effect of reducing the intensity of the beam. This energy is not lost, and some may be scattered again to re-enter the beam. At great distances from the source, the energy reaching the receiver is almost all scattered sound, out of phase with the direct sound, and arriving from a variety of directions. Consider a brief pulse of sound; for example, a single note in the trill of a bird song. At a distance from the source the direct wave from the original song will be weak. Most of the energy received will be scattered, arriving after the direct wave, and decaying with time. It is possible for the scattered sound to be *more* intense than the direct sound. Thus information useful for species identification encoded in note duration or internote interval is bound to be degraded. Wiley and Richards (1978), Richards and Wiley (1980), and Richards (1981a, 1981c) give examples of forest reverberation both in artificially produced sounds and in actual bird songs.

We localize sound by comparing time differences of onset and termination of a pulse at different ears, phase differences between ears, and intensity differences between ears. Reverberation interferes with determination of the location of a singer in two ways. First, as most of the received sound is scattered, the apparent locus of emission is broadened. Second, phase and intensity differences are confounded by the variety of complex phase and intensity fluctuations produced by multiple scattering. Since a pulse with sharp onset and termination arrives at the receiver with progressive onset and long reverberations, this cue for localization also becomes difficult to use. Eyring (1946) studied the ability of humans to localize sound in a forest. He used random firing of gunshots in selected locations, and found an error of about 20 degrees in judging the bearing of the sound. Contrary to theoretical expectation he found that error *decreases* with distance from the source in the range 300–600 feet over which his tests were conducted. Gunshot is an inherently locatable sound, with its sharp onset, and frequency transients. Bird song is probably more difficult to localize, but no studies of human ability to locate bird song have been performed. Of course, in a census, estimation of not only bearing, but distance, is important.

The effects of reverberation are not likely to be linear with distance from the source. Unfortunately an observer cannot choose the habitat to minimize the effects of reverberation (unless he only conducts censuses in open fields). Empirical measurement of the ability of observers to judge distance and bearing to playback of recorded song is necessary. Such playbacks should be done at heights above ground similar to those used by singing birds, since height can also affect sound reception. Only with measurements of this type can reliable limits be placed on transect size and number of listening points. Table 1 summarizes some of the acoustical properties of the environment. More detailed discussions of environmental acoustics and avian song communication may be found in Wiley and Richards (1978, 1981a) and Richards and Wiley (1980).

TABLE 1
EFFECTS OF ATTENUATION, FLUCTUATIONS, AND REVERBERATIONS ON BIRD SONG IN OPEN AND FORESTED HABITATS

Open

1. *Attenuation:* increases with distance, increases with sun-produced temperature stratification, decreases in midrange frequencies (1–4 kHz); limits maximum detection distance for song.
2. *Fluctuations:* increase with frequency and distance, dramatic increase with presence of air eddies caused by solar heating; cause variability in detection distance and interfere with recognition.
3. *Reverberation:* of little importance in open fields owing to absence of scattering surfaces.

Forest

1. *Attenuation:* no consistent differences from open conditions, but much less pronounced increase with solar heating.
2. *Fluctuations:* no consistent differences from open conditions, but much less pronounced increase with solar heating.
3. *Reverberation:* causes interference with both localization and recognition of songs, becomes more severe with seasonal regrowth of foliage in spring.

SONG RECOGNITION

The effects discussed thus far are often thought to interfere primarily with song *detection*. More subtle, but potentially more serious for censuses, are problems with song *recognition* caused by environmental acoustics. As a communication signal, bird song is adapted to the acoustics of the environment. It may not be the case, however, that the adaptations are for maximum locatability or discriminability. Many calls, not only alarm calls, are convergent across species, and are specialized for short distance transmission and difficulty in localization (Wiley and Richards 1981). The consequences of a mistaken identification of a few songs are less severe for a bird than for an ornithologist.

Territorial males are commonly able to individually recognize their conspecific neighbors. They sing for hours each morning, and only need listen for unusual *changes* in the singing patterns of neighbors (see Schleidt 1973). A human observer, has a more difficult recognition task. He must, in a short period, identify *all* species of singing birds from a given location. Recognition of multiple signals arriving at unknown times is one of the most difficult signal detection tasks (Green and Swets 1974, Richards 1981a). The decisions of the observer are biased by his expectations; common birds are easily identified, rare birds with songs degraded by distance may be misidentified or ignored. The task of recognition of multiple species and the time frame in which recognition takes place are so different from the communication problems faced by birds that adaptations for combating degradation may not be of great use to human observers. Other papers at this symposium address the problems of accuracy of species identification—my intent here is to draw attention to some problems of recognition occurring as a result of the acoustics of the environment.

One adaptation of bird song, facilitating detection by birds, but potentially interfering with recognition by human observers, is the separation of songs into alerting and message components (Richards 1981a). Numerous species of birds have initial song notes which converge in structure to a relatively pure-tone form. In the same species the remainder of the song is frequently extremely variable. Such species include the Song Sparrow (*Melospiza melodia*), White-crowned Sparrow (*Zonotrichia leucophrys*), Rufous-sided Towhee (*Pipilo erythrophthalmus*), and at least 15 other North American passerines. For birds the easily detectable initial note facilitates detection at a distance and may elicit an approach for recognition of the more easily degraded rapid, complex trills. In a census the observer does not have the option of a close approach. Reverberation may virtually obliterate the component of the song containing most of the species-specific information. Many of the species with this adaptation have such diverse songs that such detail is crucial for a positive species identification. To reduce the problem particular attention must be paid to training of observers in identification of the songs of multi-themed birds with alerting-note song structures, using tapes of both normal and distance-degraded songs.

Even more troublesome may be birds with songs that are easily distinguished at close range, but whose species-specific characteristics converge when the songs are degraded by distance. Again, the problem is most severe in birds with multiple and diverse themes. A Carolina Wren (*Thryothorus ludovicianus*), for example, often has at least 20 distinguishable song themes, and may have many more. Some of these are rather similar to those of Tufted Titmice (*Parus bicolor*), Northern Cardinals (*Cardinalis cardinalis*), and Kentucky Warblers (*Oporornis formosus*). Species identification by observers is often made on the basis of song "quality," rather than the specific sequence of notes. The acoustic variables in judgements of song quality are primarily the amplitude envelopes of individual notes, tremolo (rapid frequency or amplitude modulation), and high-frequency harmonic content. These are also the acoustic parameters most susceptible to degradation over a distance. Observer training on degraded as well as high quality song will help reduce misidentifications of distant song.

The acoustic problems discussed, though unavoidable, are often sufficiently predictable that they need not interfere with a census conducted by trained observers. Empirical measurements of detection distance and locatability must be made for each census area. Observers must be tested for reliability in estimation of distance and direction, and for ability to recognize degraded song.

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