

# **Final Technical Report**

## **Detection and Perception of Sound by Eagles and Surrogate Raptors**

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## List of Acronyms and Abbreviations

|                   |  |
|-------------------|--|
| ABR               | auditory brainstem response                                |
| ACP               | Advanced Conservation Practices                            |
| AM                | amplitude-modulated  |
| ASSR              | auditory steady-state response                             |
| ANOVA             | analysis of variance                                       |
| AWWI              | American Wind Wildlife Institute                           |
| BAEA              | bald eagle   |
| BGEPA             | Bald and Golden Eagle Protection Act                       |
| CAP               | compound action potential of the auditory nerve            |
| CATSS             | Center for Applied and Translational Sensory Science (UMN) |
| CN                | cochlear nuclei  |
| dB SPL            | decibels sound pressure level referenced to 20 $\mu$ Pa    |
| ECPG              | Eagle Conservation Plan Guidance (USFWS)                   |
| EtCO <sub>2</sub> | end-tidal CO <sub>2</sub> (carbon dioxide)                 |
| FM                | frequency-modulated  |
| Hz                | Hertz (cycles/sec)   |
| IPI               | interpeak interval   |
| IQR               | interquartile range  |
| kHz               | kiloHertz  |
| MBTA              | Migratory Bird Treaty Act                                  |
| MEARL             | Mobile Evoked Auditory Response Lab                        |
| MSPL              | Multi-Sensory Perception Laboratory                        |
| nMLD              | dorsolateral mesencephalic nucleus                         |
| NREL              | National Renewable Energy Laboratory (USDOE)               |
| NWCC              | National Wind Coordinating Collaborative                   |
| OBPP              | observer-based psychoacoustic procedure                    |
| SAFL              | St. Anthony Falls Laboratory (UMN)                         |
| s.d.              | standard deviation   |
| s.e.m.            | standard error of the mean                                 |
| UMN               | University of Minnesota                                    |
| USDOE             | United States Department of Energy                         |
| USFWS             | United States Fish and Wildlife Service                    |

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## Executive Summary

One overarching objective of this program of study was the accumulation of objective, scientifically valid information relating to auditory performance of bald and golden eagles that may be used to guide the development of acoustic alerting/deterrence technologies intended to discourage encroachment into wind energy air spaces. To that end, analyses aimed at the characterization of sensitivity to sound in bald and golden eagles, along with findings in the supra-threshold, dynamic frequency spaces related to response latencies and amplitudes, leads us to conclude that bald, and golden eagles navigate the same basic working auditory space, as in other known and thus far characterized members of the diurnal raptor family. Specifically, bald and golden eagles, along with other raptor species within the group, operate in an auditory space characterized by a frequency band at least four octaves wide and centered on 2 kHz, with an upper frequency limit between 6 and 10 kHz at 80 dB SPL and a lower frequency limit that almost certainly extends below 0.2 kHz. Consequently, we recommend that signal designers use these data as a guideline in efforts to design effective and efficient acoustic alerting/deterrent systems. It is important to note that signal energy broadcast outside of this frequency band at moderate levels will not contribute to the efficacy of a deterrent but will add an unnecessary fraction to the overall acoustic pollution budget. The importance of this consideration is heightened by contemporaneous concerns related to the transmission of noise broadcast by wind energy farms.

In addition, based on analyses of data acquired from red-tailed hawks using the same experimental paradigm and data acquisition system, we conclude that auditory function in the red-tailed hawk is sufficiently like that observed in bald and golden eagles to permit its use as a surrogate species. Response waveforms, threshold-frequency curves, and input-output characteristics match those of eagles closely. It should be noted however, that differences in sensitivity and slightly extended high-frequency limits of hearing should be taken into account when extrapolating findings from one species to the others. Although the inclusion of behavioral tests of red-tailed hawks to acoustic stimuli was beyond the scope of this investigation, future efforts to assess response parameters like signal-type preference and habituation rate will further elucidate their suitability to serve as eagle surrogates in behavioral studies; nonetheless, the species in question are well matched with respect to basic auditory performance.

A second essential objective of this program of study was the acoustic characterization of a subset of calls comprising the vocal repertoires of bald and golden eagles that may be used to supplement auditory performance findings in the effort to guide the development of acoustic alerting signals. With regard to that objective, the vocal repertoires of both bald and golden eagle species are rich and varied. While similar in spectrographic structure, distinctive differences are also clear. Generally, golden eagles produce some calls with shorter durations, and similar “sounding” calls exhibit distinctively different spectrographic patterns than those of bald eagles. Both species produce calls that contain a wide variety of nonlinear elements that operate to enhance the rich and varied nature of commonly observed vocal products.

Comparison of the average power spectra of commonly observed bald and golden eagle calls with threshold-frequency curves leads to the conclusion that call energies fall within the frequency bounds of hearing. Further, the acoustic energy of calls considered in this report tend to fall into overlapping, but different frequency ranges of the acoustic sensitivity curve. This condition may encourage signal designers to vary the frequency content of acoustic deterrence signals in the field.

Finally, preliminary observations relating to the tendencies and proclivities of bald eagles to attend to the acoustic landscape lead to the conclusion that eagles monitor their immediate sound environment assiduously. Individuals respond to a variety of natural and synthetic sound signals reliably and, perhaps most relevant in the context of the engineering of acoustic alerting/deterrence technologies, habituation to most sounds considered in this effort was minimal. These preliminary results, while calling for extended behavioral testing, are promising and set the stage for the exportation of behavioral studies into real world scenarios.

## **Project Motivation**

Utility scale wind energy is a clean, reliable, and competitive energy source that currently provides an estimated 4.5% of our nation's energy. Since 2006, the U.S. installed wind capacity has grown by over 50 GW with a total capacity estimated at 61 GW (U.S. Dept. of Energy [USDOE], 2015). Wind penetration is accelerating, with nearly 50% of the growth occurring over the last 8 years. The U.S. Department of Energy (DOE) as well as many state and regional agencies and industry stakeholders seek continued expansion of wind energy as a major, reliable, clean energy source for the United States. The DOE determined in their 2015 Wind Vision report that it "is both viable and economically compelling to deploy U.S. wind power generation in a portfolio of domestic, low-carbon, low-pollutant power generation solutions..." The Wind Vision study is based on an "ambitious but credible scenario" of sustained growth in U.S. wind energy sector of 10% of our nation's energy from wind by 2020, 20% by 2030 and 35% by 2050. Wind energy is a critical component to our nation's energy portfolio and, because it is a low-carbon and renewable energy source, it also has vital benefits for our planet.

***In order for the growth of wind energy to meet its full potential, barriers to growth must be identified and solutions developed.*** The DOE, among other organizations, seeks solutions to challenges associated with bald and golden eagle mortality resulting from collisions with wind turbines, which is one of the main environmental barriers to expansion of wind energy (USDOE, 2015). The issue of avian mortality, in general, has long been an area of concern with development of utility scale wind farms. For example, the Altamont Wind Resource Area in California was an early wind development that resulted in many raptor deaths from blade strikes (Smallwood and Thelander, 2005). Through repowering of this and other sites (i.e. removing outdated turbines and installing larger, more advanced turbines) the numbers of turbines are reduced, siting is improved and avian deaths have decreased; but concerns over avian mortality remain a high priority for our nation.

One of the three strategic activities identified in the 2015 Wind Vision study is expanding the developable areas for wind power. Wind development will seek untapped high-quality resource areas such as sites accessible with new transmission lines, low wind sites, or sites that require careful consideration of wildlife, human, or environmental impacts (USDOE, 2015). As wind energy seeks to expand, there will be more overlap between the geographic range of eagles and wind energy projects (AWWI, 2014). This will lead to a greater need for solutions that allow co-existence of eagles and wind plants.

***Federal law prohibits taking of eagles.*** The Bald and Golden Eagle Protection Act was enacted by the federal government in 1940 and prohibits killing of eagles without a permit. In September 2009, the Department of the Interior released Eagle Permits; Take Necessary to Protect Interests in Particular Localities, which is referred to as the "Eagle Rule." The ruling provides a process by which an entity may obtain permits for incidental taking of eagles. This ruling was further clarified in 2013 with the release of

the Eagle Conservation Plan Guidance (ECPG) (USFWS, 2013). This guidance provides an adaptive management-based approach for estimating eagle take and reducing takes. Incidental take permits, in principle, can be obtained through this process.

A key component of the 2013 ECPG is the need for project developers to provide Advanced Conservation Practices (ACPs) to help minimize impacts of eagles with wind turbines. ACPs are defined generally as “scientifically supportable measures that are approved by the [USFWS] and represent the best available techniques to reduce eagle disturbance and ongoing mortalities to a level where remaining take is unavoidable” (50 CFR 22.3). Presently, there are no ACPs formally approved by the USFWS but examples include siting considerations, minimizing avian perch sites, reducing prey habitat, adjusting turbine operational protocols, and deployment of detection and deterrent technologies.

***Technology-based solutions are a possible means of reducing eagle mortality at wind plants.*** Through this FOA, the Department of Energy seeks to support the advancement of technology based ACPs. Wind turbines and wind plants are highly advanced systems with existing real-time monitoring systems in place. Wind turbines themselves are autonomous machines that self-monitor their health and operational performance and include sophisticated safety systems that allow rapid shut-down of the machine in case of system failure/fault. It is natural to consider extending the health monitoring systems of the turbine to include environmental monitoring of the adjacent space surrounding the wind plant. Surveillance technologies, cameras, radars, and thermal detection can be used to detect and identify aves within the vicinity of a wind plant. Deterrent technologies can be coupled with the detection systems to warn and divert birds away from the turbine hazard.

A workshop was held by the U.S. DOE National Renewable Energy Laboratory (NREL) in December 2015, Wind Energy Industry Eagle Detection and Deterrents: Research Gaps and Solutions focused on the state-of-the art of these technologies (Sinclair and DeGeorge, 2016a). Participants ranged from industry, agency and academia. The outcomes of the workshop provide guidance on needs, priorities and next steps for technology based ACPs. A few key outcomes include:

- A small number of technologies exist today for detection and even fewer for deterrence.
- Participants placed a high level of priority on supporting new research on eagle’s sensory systems, perceptions, and response to stimuli. Information from more basic research is “critical to developing effective deterrent system”.
- Participants focused on identifying attributes of needed yet-to-exist or early-stage technologies (e.g. species identification, increasing area of coverage, cost-effectiveness) and the need for independent field testing and validation.

Regarding validation of technologies, another NREL report (Sinclair and DeGeorge, 2016b) concludes that field validation is a challenge because of the rare occurrence of eagles. The authors suggest that expanding the taxa included in a study could help achieve statistical validation. Our project includes analysis of red-tailed hawk hearing along with the eagle evaluations. Our working thesis hypothesized that red-tails have similar hearing characteristics and therefore can serve as a viable surrogate species for acoustic-based technology validation.

***Sound-based deterrent systems are a viable pathway for reducing eagle mortality, yet we have very little knowledge on the auditory systems of bald and golden eagles.*** The auditory system is a primary sensory system of the eagle yet very little research has been conducted on it to date. The NREL workshop

concluded that research on the eagle's auditory system was a high priority for this field and would open the door to possible new deterrent approaches (Sinclair and DeGeorge, 2016a). In this project we conduct a one-year research program to study the auditory system of bald and golden eagles in order to provide, for the first time, science-based data to support development of advanced, acoustic-based deterrent technologies.

## Project Objectives

The primary goal of this project was to assess auditory sensitivity in golden and bald eagles as an essential first step in the effort to establish acoustic alerting/deterrence methodologies designed to diminish collisions with wind turbines. We also conducted assessments on red-tailed hawks as a potential surrogate species for future technology validation. The project was designed to provide information in a form that is relevant and easily transferrable to technology development communities, specifically those involved in developing detection and deterrence technologies for eagles and other birds at wind plants, hydropower facilities, airports and other structures. We defined eleven objectives for this project.

- **Objective 1:** Assess auditory sensitivity in golden and bald eagles as well as the red-tailed hawk using standard auditory brainstem response (ABR) methodology.
- **Objective 2:** Generate and compare mean threshold vs. stimulus frequency plots (audiograms) for each species tested.
- **Objective 3:** Generate comparative audiograms for juvenile and adult bald eagles.
- **Objective 4:** Assess supra-threshold auditory performance using ABRs, including analyses of peak latencies, interpeak intervals and peak amplitudes as a function of stimulus level and frequency for each species studied.
- **Objective 5:** Compare hearing sensitivity curves to examples of the spectra of noise produced by a single wind turbine and a wind turbine farm to guide the development of alerting/deterrence technologies.
- **Objective 6:** Assess supra-threshold auditory performance using auditory steady state responses to complex amplitude modulated (AM) and frequency modulated (FM) stimuli.
- **Objective 7:** Develop a state-of-knowledge synthesis report on eagle vocalization and response to auditory cues.
- **Objective 8:** Collect and analyze recordings of vocalizations produced by bald and golden eagles to identify salient features of calls that are part of their vocal repertoires to guide the development alerting/deterrence technologies.
- **Objective 9:** Identify natural signals and other auditory stimuli that result in measurable behavioral responses in eagles to guide the development of alerting/deterrent system technologies.
- **Objective 10:** Publish research findings in at least one peer-reviewed journal (e.g. *Journal of the Acoustic Society of America*, *Journal of Comparative Physiology*).

- **Objective 11:** Publish a research report on the project for application to wind energy detection and deterrence technologies. The report will be published as a DOE report or in a wind energy peer-reviewed journal (e.g. *Wind Energy*, *Renewable Energy*).

## Project Team

Our project team has expertise from diverse fields of engineering, biology, veterinary medicine, auditory physiology, and psychoacoustics along with facilities for specialized raptor care and auditory research. The project was led by an experienced project manager. Here we summarize the primary investigators and the facilities that were utilized in this project.

**Jeffrey Marr MS PE, Associate Director, St. Anthony Falls Laboratory, UMN** – Marr served as Principal Investigator (PI) with responsibility for oversight of management and reporting for the effort. He is also Associate Director of the Eolos Wind Energy Research Program and served as project manager for the design, construction and operation of the Eolos Wind Energy Field Station (DE-EE0002980, see Section 4.2). Marr provided input on wind energy technologies and wind turbine/plant operation as they may relate to the study of eagle hearing, and development of detection and deterrent technologies.

**Edward Walsh, PhD, Contractor** – Walsh served as an investigator on the project. He is the former Director of the Developmental Auditory Physiology Laboratory at the Boys Town National Research Hospital (BTNRH), Director of the Physiology Phenotyping Core at BTNRH and has over 30 years of experience working in the field of auditory neuroscience. His work has been carried out primarily at the systems' physiology level and he has extensive experience recording from single auditory nerve fibers, from individual neurons in the central auditory system, as well as recordings of cochlear potentials, near- and far-field evoked potentials, and distortion product and stimulus frequency otoacoustic emissions. Dr. Walsh is currently a Senior Research Scientist at the VA Loma Linda Healthcare System.

**JoAnn McGee PhD, Contractor** – McGee served as an investigator on the project. She is the former Director of Animal Science at the Boys Town National Research Hospital (BTNRH) and former Co-Director of the Physiology Phenotyping Core at BTNRH and has collaborated with Dr. Walsh for over 3 decades in the field of auditory neurophysiology and pharmacology. Dr. McGee has expertise in the areas of peripheral and central auditory biology and has conducted electrophysiological studies ranging from single auditory nerve fiber recording to studies of individual neurons in the central auditory system. Her expertise also includes evoked potential and distortion product and stimulus frequency otoacoustic emissions methodologies. Dr. McGee is currently a Senior Research Scientist at the VA Loma Linda Healthcare System.

**Julia Ponder DVM, Associate Professor, College of Veterinary Medicine; Executive Director, The Raptor Center, UMN** – Ponder served as co-PI on this project with responsibility for design of laboratory testing of eagles and other surrogate birds. Through her role at The Raptor Center, Ponder was also responsible for access to test subjects and the animal care protocols and permitting required to carry out the testing program. She has a DVM degree from Texas A&M University and an MPH from University of Minnesota. In addition to her clinical work with raptors, her research is focused on the wildlife health component of Ecosystem Health, raptors as sentinels for infectious disease and environmental contaminants, and identifying emerging issues related to raptor health and populations. She has worked with endangered and threatened raptor populations and has consulted globally on raptor health issues.

**Peggy Nelson, Professor and former chair, Department of Speech-Language-Hearing Science, UMN** – Nelson served as co-PI on this project with responsibility for the design of the program of auditory testing. Nelson is director of the Center for Applied and Translational Sensory Science (CATSS) and the

Multi-Sensory Perception Lab (MSP). She has taught and conducted NIH-funded research since 2000. She has been a clinical audiologist for 30 years. Nelson has a PhD from the University of Kansas and did post-doctoral work at Gallaudet University and the University of Maryland. Her research focuses on hearing loss and the problems of understanding speech in noise by a variety of populations, including children in schools, hard-of-hearing listeners, hearing aid users, and cochlear implant listeners. She is vice-president for research and scholarship for the Council of Academic Programs in Communication Sciences and Disorders. She is a Fellow of the American Speech-Language-Hearing Association and the Acoustical Society of America.

**Patrick Redig, DVM, PhD, Professor, Founder and former Director of the Raptor Center** – Redig served as co-PI on this project with responsibility for design of laboratory testing of eagles and other surrogate birds. He is a Professor in the Department of Veterinary Clinical Sciences at the University of Minnesota, College of Veterinary Medicine. He is also the Founder and Director Emeritus of The Raptor Center at the University. Redig earned his Bachelor of Science degree from St. Cloud State University and his Doctorate of Veterinary Medicine from the University of Minnesota. He completed a PhD in physiology at the University of Minnesota. Since the 1970s, Redig has contributed to the growing field of avian medicine through innovation in a host of bird-related concerns, from housing and feeding to anesthesia, radiology, orthopedic surgery, endoscopy as well as our understanding of key infectious diseases, especially aspergillosis. He has developed and disseminated well-proven methodologies in the medical and surgical management of raptors.

**Chris Feist, Associate Engineer, Saint Anthony Falls Laboratory, University of Minnesota** - Chris Feist was responsible for acoustic recordings of eagle vocalizations, sound attenuation testing of MEARL, technical support, and project management. His background is aerospace engineering and mechanics and has 9 years of research experience in wind energy including fluid mechanics and acoustics.

**Chris Milliren, Associate Engineer, Saint Anthony Falls Laboratory, University of Minnesota** - Milliren provided technical support and project management on this project. He has 8 years of research experience in the field of wind energy and has been an integral part of the team that manages the University of Minnesota's Eolos wind energy research field station. In this project Milliren designed and fabricated the MEARL and transported it to Cyril, OK.

**Eleanor Arpin** - Arpin is an undergraduate research student at the University of Minnesota in the department of biosystems and bioproducts engineering. Her role on the project involved video editing and analyses of data collected in Phase 3 of the project.

## Overview of Research Program

The project was carried out in three phases described in detail in subsequent sections:

- Phase I: Auditory performance was characterized in bald and golden eagles and red-tailed hawks;
- Phase II: The acoustic properties of a select library of vocalizations recorded from bald and golden eagles were characterized;
- Phase III: A pilot behavioral study was conducted to assess responses of bald eagles to a select set of natural and synthetic acoustic stimuli.

## Phase I – Auditory Performance in Bald Eagles, Golden Eagles and Red-tailed Hawks

### Overview

The design of research reported here called for the comprehensive characterization of the hearing capabilities of bald (*Haliaeetus leucocephalus*) and golden (*Aquila chrysaetos*) eagles. Our approach relied heavily on measurements of the auditory brainstem response (ABR) to tonal stimuli spanning the responsive frequency range of the species under investigation. The ABR is a relatively non-invasive tool commonly used to assess auditory sensitivity, as well as supra-threshold auditory response characteristics, in a wide range of vertebrates, including a variety of avian species.

The typical ABR consists of 4 to 5 highly replicable peaks that reflect the voltages produced by the synchronized responses of neurons of the auditory nerve and lower brain regions responsible for processing sound related information. The response occurs within the first 10 ms, or so, following an acoustic stimulus (Figure 1). Wave I is generally the largest and is produced by sound driven activity in the auditory or eighth (VIIIth) cranial nerve. Successive waves reflect, primarily, the sequential activation of increasingly rostral (i.e., more centrally located) auditory nuclei up to and including midbrain neurons. Because the voltages produced by the brain are small (i.e., are in the microvolt range), responses to multiple presentations of the same stimulus must be averaged to visualize the response.

The procedure for recording ABRs involves anesthetization of test subjects to maintain a quiet recording environment. Three small subdermal sensors, or electrodes, are positioned at specific locations on the bird's scalp and shoulder during recording sessions (Figure 2). A series of acoustic stimuli (e.g. broadband clicks and frequency-specific tone pips) are delivered via a speaker positioned a fixed distance above one ear. Responses are recorded and displayed in real time and further processed following data acquisition.

Following recording sessions, test subjects are monitored while recovering fully from anesthesia and are subsequently returned to their housing facilities. Test subjects included wild bald eagles admitted to the Raptor Center for treatment, as well as resident golden eagles located at Sia, The Comanche Nation Ethno-Ornithological Initiative in Cyril, Oklahoma. A full description of testing procedures is included in Appendix A.

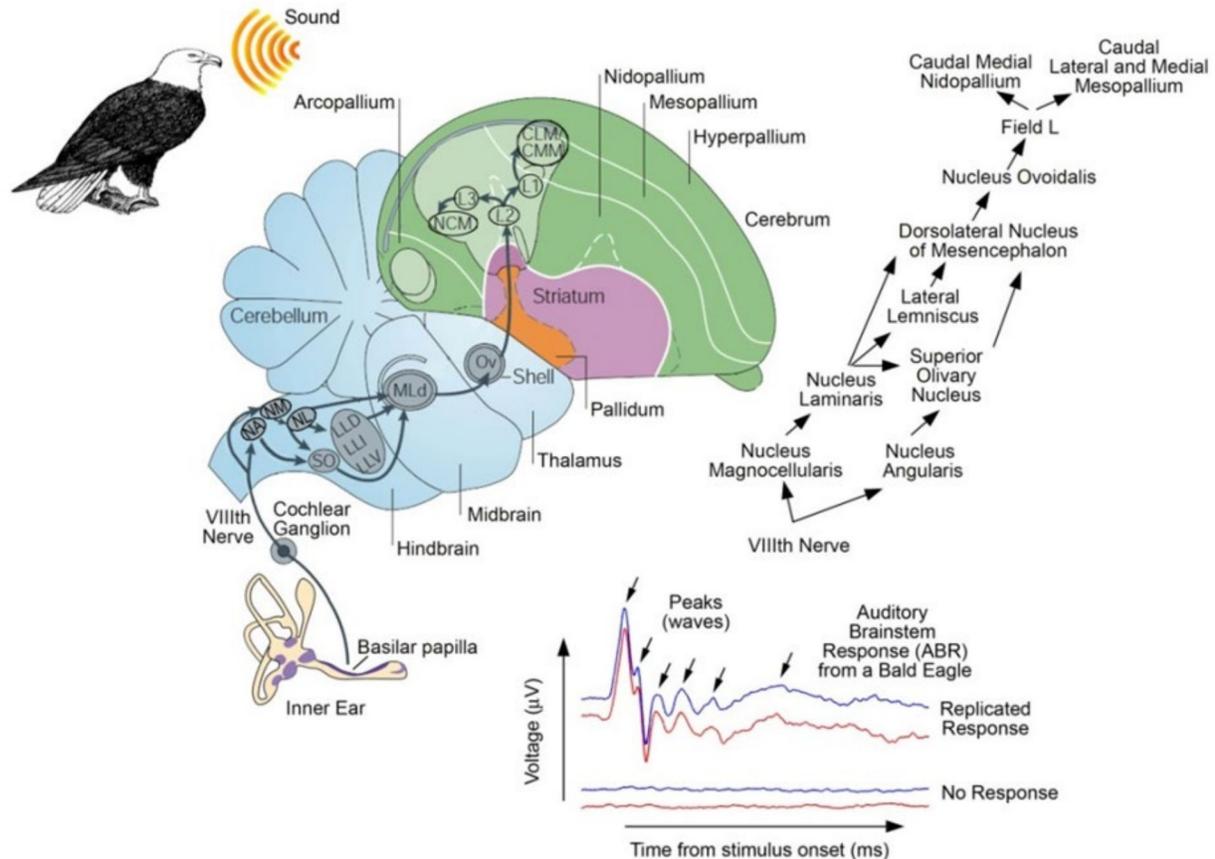


Figure 1. An example of an auditory brainstem response (ABR) recorded from a bald eagle is shown in the lower right. ABR peak I is produced by sound activated auditory nerve fibers, and successive ABR peaks represent the sequential activation of more centrally located nuclei, indicated as circled areas within the auditory brainstem cartoon. The schematic of the avian brain was adapted from Jarvis *et al.* (2005).

Results of a portion of this work were published in a peer-reviewed journal article entitled “Auditory performance in bald eagles and red-tailed hawks: a comparative study of hearing in diurnal raptors” (McGee *et al.*, 2019c).

### The Red-tailed Hawk as a Potential Eagle Surrogate

In addition to evaluation of bald and golden eagles, auditory performance in red-tailed hawks (*Buteo jamaicensis*) was evaluated to determine their potential value as a hearing surrogate. The rationale underlying this action plan centered on the concern that access to eagles might be limited, and that red-tailed hawks might serve as proxy for eagles if their auditory performance attributes are suitably comparable.

### Study Locations

Studies were conducted in two locations dictated primarily by the location and availability of captive raptors. The first location was the Multi-Sensory Perception Laboratory (MSPL) located at the University of Minnesota (UMN), which is designed specifically for studies focused on hearing and is in close proximity to the UMN Raptor Center. The Raptor Center’s primary focus is the rehabilitation of injured raptors but also serves as an educational facility. The MSPL houses a double-walled, electrically-shielded, sound-attenuating chamber lined with acoustic foam that was used to assess auditory function in

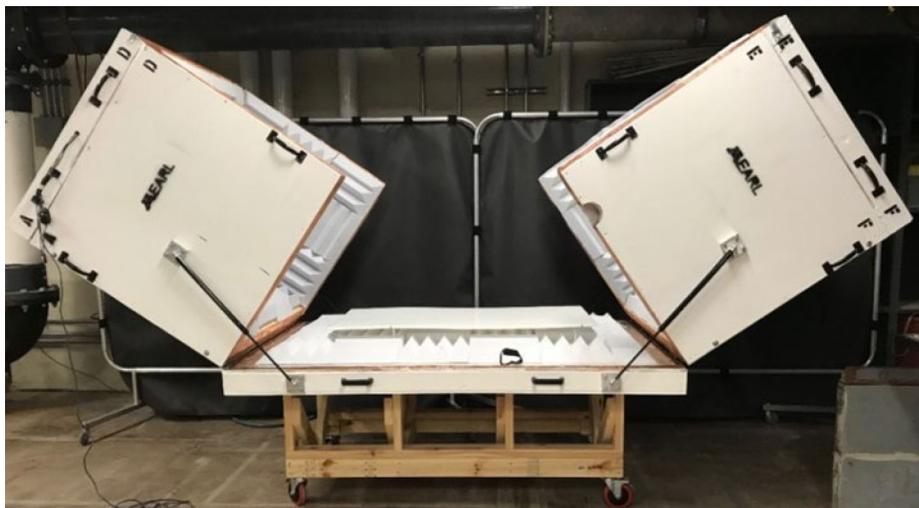
raptors transported from the Raptor Center (Figure 2). Both bald eagles and red-tailed hawks were studied in the sound-attenuating chamber at the MSPL.

The second recording space used in this investigation was an acoustic-foam lined and electrically-shielded testing chamber designed specifically for this project (Figure 3), known as the Mobile Evoked Auditory Response Lab (MEARL). The MEARL was transported to Cyril, Oklahoma to assess auditory function in golden eagles located at Sia, The Comanche Nation Ethno-Ornithological Initiative. Sia is an organization committed to the preservation of Comanche Nation culture as well as those of other Native American tribes/nations. These practices include the use and distribution of eagle feathers acquired from molting captive eagles.

The attenuating power of MEARL was assessed by placing a recording microphone on the subject platform (see Appendix B) inside the chamber and broadcasting a continuous pink noise signal into the space outside the chamber. The attenuating power was determined by subtracting sound levels of broadcast acoustic signals with MEARL in both closed and open states. The signal was attenuated by approximately 50 dB at frequencies above 100 Hz when the broadcast signal was delivered at 90 dB Leq, and by approximately 30 dB at all frequencies above 100 Hz when the broadcast signal was delivered at 70 dB Leq (Figure 4).



**Figure 2. Photograph taken inside the sound-attenuating booth in the Multi-Sensory Perception Laboratory (MSPL at the University of Minnesota (UMN). The anesthetized bird is a juvenile bald eagle being prepared for a recording session.**



**Figure 3. Photograph of UMN's Mobile Evoked Auditory Response Lab (MEARL) shown fully open (left and right halves pivot open). The flat platform in the center is used to support the test subject and audio transducer (speaker) during recording sessions.**

signal was delivered at 70 dB Leq (Figure 4).

These results led to the conclusion that environmental noise was adequately attenuated to support meaningful electrophysiological studies. Additional confidence that MEARL served as an acceptable workspace was gained by studying individual raptors in both MSPL booth and

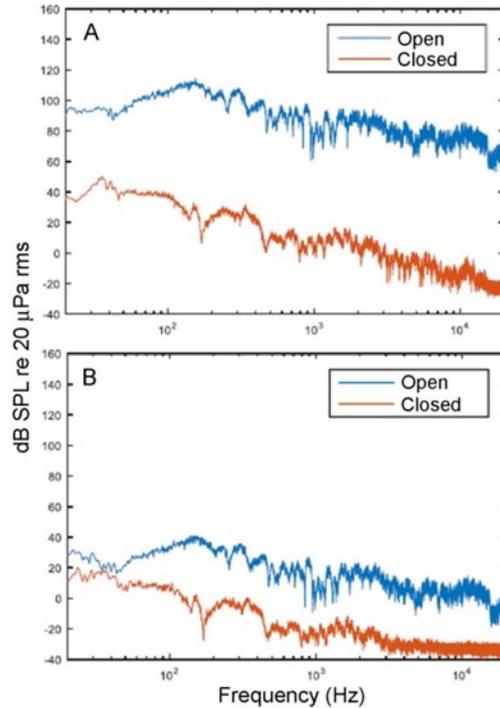
MEARL environments. Differences were within measurement error, confirming the validity of the conclusion drawn from attenuation power estimates.

## Materials and Methods

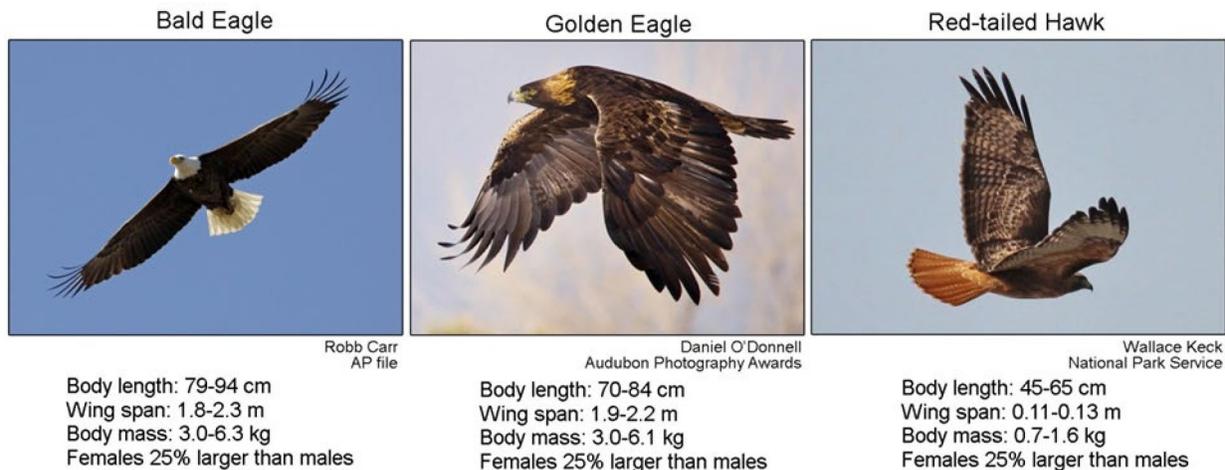
Photographs and the general physical characteristics of the species studied are shown in Figure 5. A total of nine (9) bald eagles ranging in age from the year of hatching to adulthood were tested. Additionally, seven (7) red-tailed hawks, ranging in age from the hatch year to the second year, and nine (9) golden eagles, ranging in age from 2 to 9 years of age, were tested (Table 1). Males and females of each species were included in the study. All of the bald eagles and red-tailed hawks were wild birds admitted to the Raptor Center for treatment and were in the final stages of rehabilitation prior to release. Golden eagle subjects included a mix of captive-bred, egg-rescued and captive-raised individuals, as well as wild birds maintained in captivity (Table 1).

Animals were anesthetized with isoflurane to eliminate muscle activity and thereby maintain a stable, quiet recording environment. Platinum subdermal needle electrodes were positioned at the vertex (active, noninverting), in the region of the tympanic ring (reference, inverting) and in the bird's clavicular region (ground) to differentially record free-field sound-evoked responses.

The transducer, a multi-field magnetic speaker (TDT MF1), was positioned 10 cm above one ear (typically the right ear). Stimuli were symmetrically shaped, 3 ms long tone bursts, 1 ms raised cosine on/off ramps with 1 ms plateau, and 64  $\mu$ s long click; duration was increased to 9 ms, with 3 ms on/off ramps when acquiring data for the 354 Hz stimulus.



**Figure 4.** Frequency spectra of the signal measured within the MEARL when doors were open (blue) and closed (red). The signal was pink noise presented at 90 dB Leq (A) and 70 dB Leq (B).



**Figure 5.** Photographs and general physical characteristics of each of the species included in the investigation.

Scalp potentials were amplified 100,000X, bandpass filtered between 0.03 and 10 kHz, and sampled at a 20 kHz rate over a 15 ms time epoch. Responses were replicated for each stimulus condition.

**Table 1. Subject Characteristics**

| Bald Eagles |       |                | Red-tailed Hawks |       |                | Golden Eagles |               |                             |
|-------------|-------|----------------|------------------|-------|----------------|---------------|---------------|-----------------------------|
| Sex         | Stage | Body Mass (kg) | Sex              | Stage | Body Mass (kg) | Sex           | Age (y)       | Source                      |
| F           | HY    | 4.30           | F                | HY    | 1.25           | F             | 2             | Captive bred                |
| F           | HY    | 4.42           | F                | SY    | 1.23           | F             | 5             | Captive bred                |
| F           | SY    | 4.25           | M                | HY    | 0.78           | F             | 5             | Egg rescue - captive raised |
| F           | Ad    | 4.56           | M                | HY    | 1.00           | F             | 5             | Wild origin (NE)            |
| F           | Ad    | 4.77           | M                | HY    | 1.03           | F             | 5             | Wild origin                 |
| M           | HY    | 3.41           | M                | HY    | 1.12           | M             | 7             | Wild origin (UT)            |
| M           | HY    | 3.73           | M                | SY    | 1.00           | M             | 7             | Captive bred                |
| M           | HY    | 3.77           |                  |       |                | M             | 7             | Captive bred                |
| M           | SY    | 3.83           |                  |       |                | M             | 9             | Wild origin                 |
| F           |       | $\bar{X}=4.46$ | F                |       | $\bar{X}=1.24$ | F             | $\bar{X}=4.4$ |                             |
| M           |       | $\bar{X}=3.69$ | M                |       | $\bar{X}=0.99$ | M             | $\bar{X}=7.5$ |                             |

Abbreviations: F, female; M, male; HY, hatching year; SY, second year; Ad, adult;

## Results

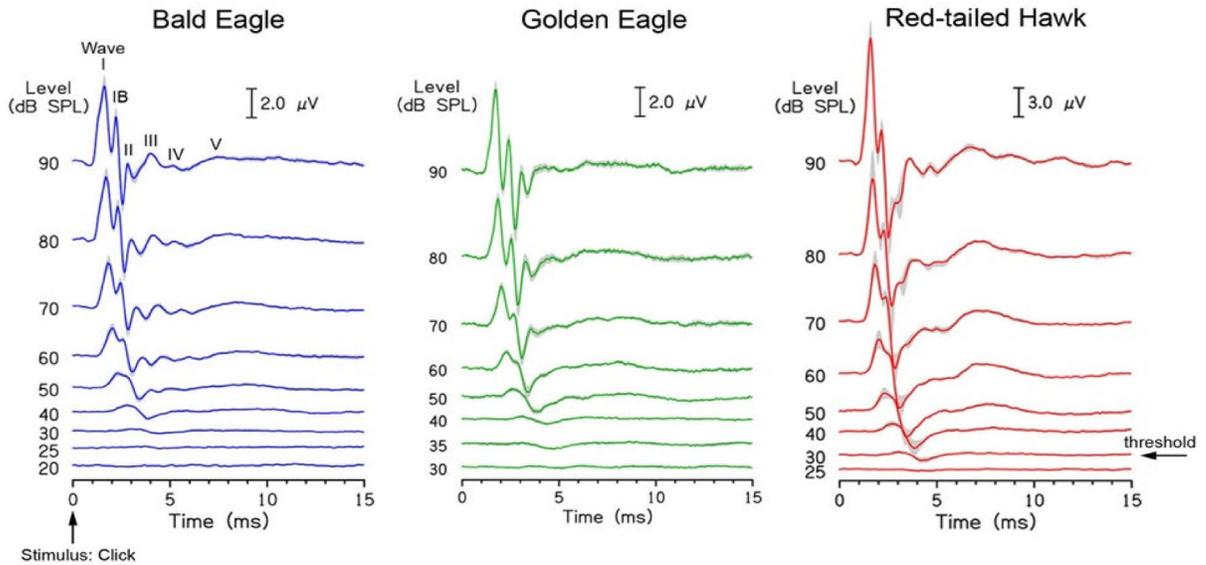
### ABR Waveforms

The auditory brainstem response (ABR) was the data acquisition workhorse of the project. ABR waveforms to click stimulation (brief, transient stimuli) are shown for each of the species included in the study in Figure 6. For each group of waveforms, the x-axis is time in milliseconds (ms) from the onset of the acoustic stimulus. The voltage scale for waveforms representing each species is shown near the top of each column. Waveforms throughout the dynamic response range, i.e., from the highest sound pressure level (SPL) delivered, which was 90 dB SPL, to progressively lower level stimuli, are shown in Figure 6. Waves, commonly referred to as peaks in this report, are labeled with Roman numerals I to V, as shown for the bald eagle response to 90 dB SPL in the left, uppermost waveform example. Note that peak I typically consisted of two maxima (i.e., was double-peaked), and the two peaks generally merged to form a single composite peak as stimulus level was reduced; the two maxima were therefore labeled waves IA and IB.

Also note that as sound pressure level decreased, peak amplitudes decrease and eventually fade into the background noise of the recording system. Estimates of response “threshold” values, defined as the lowest stimulus level capable of eliciting a visible and replicable waveform peak, were also determined for each subject. In addition, the time between the initiation of the stimulus ( $t = 0$  ms) and the appearance of the first peak is defined as response latency, the value of which increases as stimulus level is lowered.

ABRs acquired to a tonal stimulus, 2 kHz specifically, are shown in in Figure 7 for each species included in the study. Tone pips elicit responses that are similar to those observed using click stimuli, however,

minor variations in waveform architecture are observed across stimuli and, to a lesser extent, species. While thresholds provide information regarding the sensitivity of the birds to click and tonal stimuli, peak latencies and amplitudes provide information in the supra-threshold response realm.

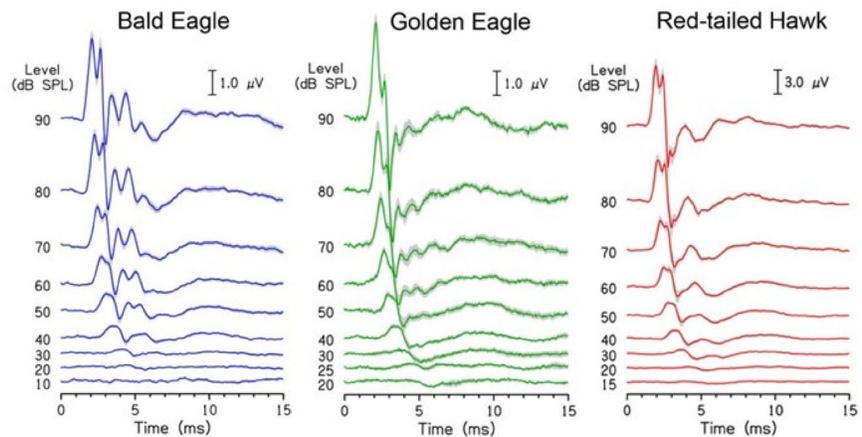


**Figure 6.** ABR waveforms averaged across individuals are shown for each of the species studied in response to click stimuli at levels ranging from 90 dB SPL (top traces) to below threshold (bottom traces). Gray shading indicates mean  $\pm 1$  s.e.m. Note the difference in voltage scale for the red-tailed hawk.

Responses like those shown in Figure 7 were acquired over a wide range of frequencies, and ABR thresholds for each subject were measured, averaged, and used to support follow-on analyses.

### Response Thresholds

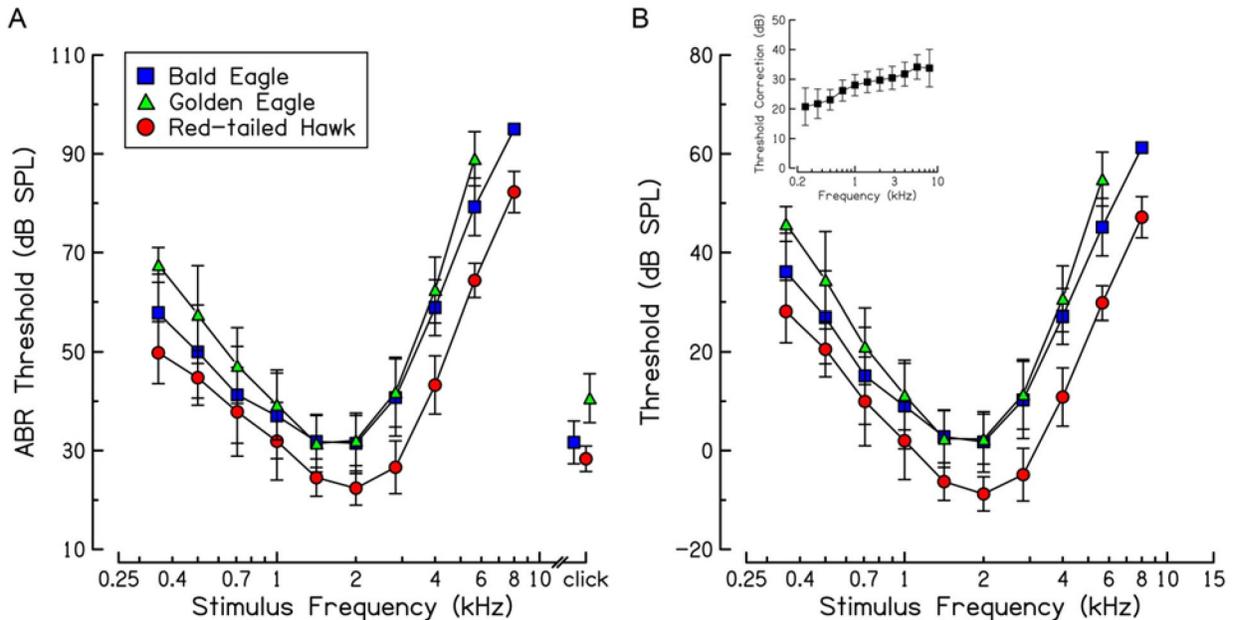
As pointed out above, the auditory threshold for a given frequency is the lowest sound level (measured in dB SPL) capable of eliciting an ABR peak that is just detectable and reproducible. In Figure 8A, average frequency-threshold curves, otherwise known as audiograms, representing species studied here are shown with error bars depicting one standard deviation (s.d.). Threshold



**Figure 7.** ABRs recorded in responses to 2 kHz tone pips for each of the species studied. The format of the graph is similar to that used in Figure 6. Note that the voltage scale for red-tailed hawks differs from that used for the eagles.

curves are convex in shape and are remarkably similar across species. All species were most sensitive to a band of frequencies between 0.5 and 3-4 kHz as measured 20 dB above the lowest threshold, which was 2.0 kHz for all three (3) groups. Thresholds in all three species drop off rapidly at frequencies below and

above 2 kHz, with the upper frequency limit being 5.7 and 8 kHz for eagles and red-tailed hawks, respectively. Thresholds in the high-frequency flank of the curve rolled off at a higher rate than those in the low-frequency flank for all subjects. Bald eagles were generally more sensitive at lower frequencies than golden eagles, whereas red-tailed hawks were more sensitive across the entire frequency range than either eagle species. Hawk thresholds were approximately 5 to 15 dB lower than those of either eagle species across the frequency range.



**Figure 8. A:** Averaged ABR thresholds ( $\pm 1$  s.d.) are plotted as a function of stimulus frequency and for click stimuli for each species included in the investigation. Note that a single bald eagle responded to 8 kHz. **B:** To compensate for temporal integration, a threshold-frequency correction curve (inset) was generated to equate evoked potential thresholds to absolute thresholds. The threshold-frequency correction curve was subtracted from each ABR threshold-frequency curve to generate threshold-frequency curves that better match actual behavioral thresholds.

Based on this sensitivity difference, enhanced effectiveness of lower level alerting signals might be expected in the case of red-tailed hawks relative to the performance of either bald or golden eagles. As an extension of this observation, red-tailed hawks may be capable of detecting alerting signals at distances further from the source when compared with the performance of eagles. However, the relative advantage gained by greater sensitivity would be, in all probability, inconsequential when assessing alerting signal efficacy, a suggestion reinforced by the fact that human hearing is generally regarded as clinically ‘normal’ when sensitivity is within 15 – 20 dB of the average sensitivity of a population of age-matched individuals with normal hearing.

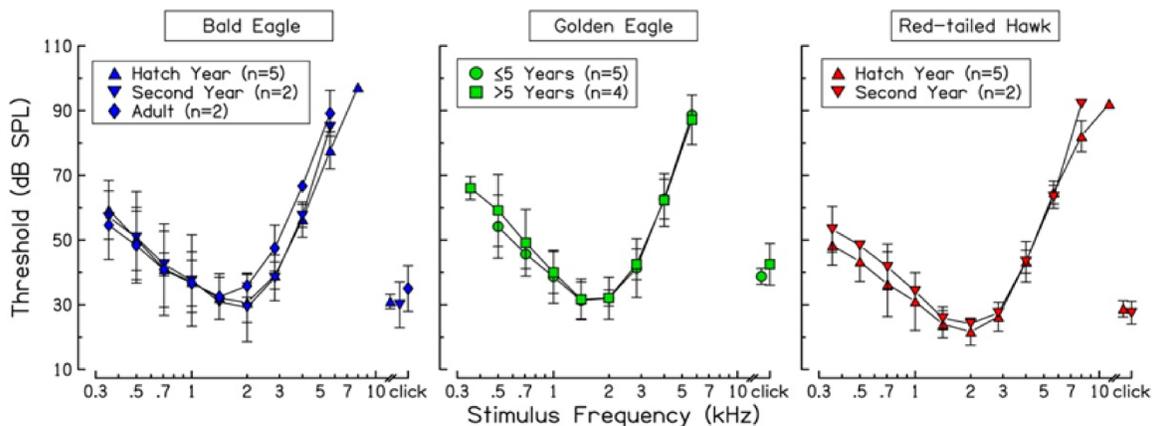
Because ABRs are synchronized responses representing the summed electrical activity of auditory neurons located in auditory centers throughout the brain, the most effective stimuli are tone pips and clicks, and the response is not affected by stimulus duration. Clicks are transient, pulsatile signals with abrupt onset/offset properties, are typically under 100  $\mu$ s in duration and elicit neural activity across a broad frequency range. Tone pips are short duration sinusoidal signals with ramped onsets and offsets to reduce frequency splatter. As stated earlier, in this study clicks were 64  $\mu$ s in duration and tone pips were generally 3 ms long with 1 ms rise/fall times and a steady-state plateau of 1 ms.

When considering auditory responses in perceptual terms and in awake animals, it is well-known that the detection of short-duration signals is diminished (thresholds are higher) relative to long-duration signals.

In other words, thresholds to acoustic stimuli are progressively elevated as stimulus duration decreases for values below approximately 200 ms.

The improvement in thresholds with increasing signal duration is a consequence of the auditory system's capacity to summate or integrate sound-induced neural activity over time, a phenomenon known as "temporal integration." Above ~200 ms, thresholds remain steady regardless of further increases in stimulus duration. Therefore, to compensate for temporal integration, a threshold-frequency correction curve was generated (inset of Figure 8B) to permit a more accurate estimate of absolute sensitivity (See Appendix C for a detailed consideration of the approach used to generate the correction curve).

Audiograms of each species were also compared across different age groups (Figure 9) and between sexes (male versus female). Statistically significant differences were not observed, although sample sizes for different age groups were unavoidably low.



**Figure 9.** Average threshold-frequency curves ( $\pm 1$  s.d.) representing age at the time of study are shown for each of the species studied. Note the difference in the specified age range for golden eagles relative to bald eagles and red-tailed hawks.

The essential conclusion of this aspect of the larger study is that threshold data reported here clearly represent an essential engineering element in the design and configuration of acoustic alerting/deterrent technologies.

### Supra-threshold Response Performance

Essential as sensitivity estimates are to alerting/deterrence signal designers, supra-threshold response performance may also play a meaningful role in the development of effective technologies. Relevant findings in this realm are considered in this section.

#### *Level-Dependence of Response Latencies*

One key element of auditory performance generally, centers on response delays following an acoustic event. Aside from air transmission time, the time required for detection of an airborne sound is governed by the transmission time of sound-induced energy through the middle ear and the time consumed in the process of converting the mechanical energy transferred by the middle ear to the inner ear into physiologically meaningful bioelectricity. This time interval is represented by the timing, or latency, of peak I of the ABR, a peak produced by the summed activity of auditory fibers in the auditory nerve activated by sound stimulation. As shown in Figure 10, response delays are strongly dependent on stimulus level regardless of stimulus type or frequency; longer delays are associated with low-level

stimuli relative to the longer response times associated with higher-level stimuli. Overall, latencies decrease steadily with increasing level and are generally similar among the three species studied here.

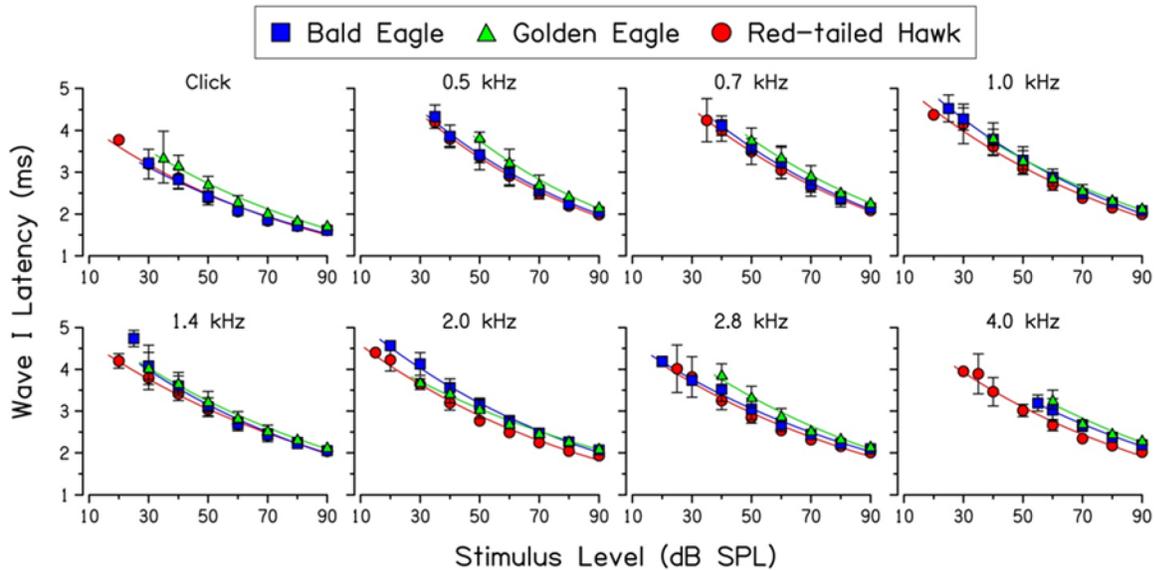


Figure 10. Average ABR wave I latencies ( $\pm 1$  s.d.) are shown as a function of stimulus level in response to clicks (upper left) and for tone pips from 0.5 kHz to 4.0 kHz in 0.5 octave steps for the three species studied here. Exponential curves were fitted to each data set.

Similar findings are associated with response components originating in more central regions of the brain and represented by ABR peaks II through V (Fig. 11). The timing of response components representing centers located deeper in the auditory brainstem (i.e., more rostral centers) are delayed relative to peak I; that is, delays associated with later-occurring peaks reflect neural transmission times between adjacent central auditory centers. Response latencies shown in Figure 11 were elicited by varying stimulation levels of the most sensitive frequency, 2 kHz, for each of the species studied.

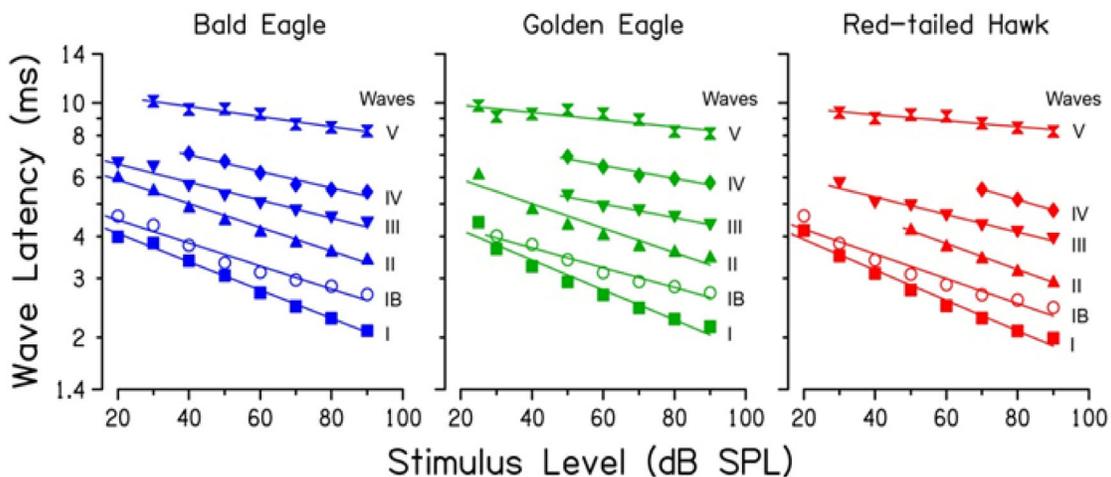


Figure 11. Latencies of each peak or wave of the ABR in response to 2 kHz are plotted as a function of stimulus level for each species. Measurements were made from the waveforms pooled across individuals from each group. Data sets have been fitted with exponential curves. Note that the y-axes are scaled logarithmically.

The clearest and most notable observation reported here is the similarity of latency-level curves for each ABR peak in each species studied. Results from responses to click and other tonal stimuli followed the same pattern (data not shown).

### *Interpeak Intervals and Response Timing*

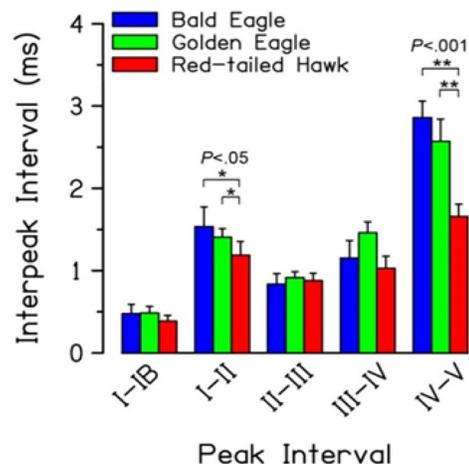
Another way of looking at response timing associated with the central processing of sound related information is to consider interpeak intervals (IPIs). IPIs represent the time delays between the activation of successive auditory nuclei as auditory information propagates through increasingly central regions of the brain, as shown in Figure 12 for the 2 kHz stimulus condition. In this figure, interval estimates are reported as mean values across stimulus level and variability is reported in standard deviation units.

The timing of transmission intervals between auditory nuclei is governed by two factors, neural conduction delay and synaptic delay. Neural conduction time is determined by the conduction velocity of the propagating neural impulse and the length of the projection between adjacent auditory nuclei. Synaptic delay refers to the time required for one neuron to pass information to another neuron, an event typically lasting approximately 1 ms, although some synapses within the central nervous system are capable of operating in the submillisecond range.

Given the short nature of the IA-IB IPI reported here (~0.45.ms) and the merging of the peaks at low levels, one can generally infer that peaks IA and IB both represent stimulus driven discharge activity of auditory nerve fibers; i.e., the IA-IB interval is not likely influenced by synaptic activity. Intervals of ~0.88 ms between II and III and ~ 1.21 ms between waves III and IV are generally consistent with synaptic delays, while the longer IV-V delay may reflect more complex neural processing circuitry in the midbrain region.

IPI differences between eagle species included in this investigation were not significant, regardless of the IPI under consideration. However, the interval between peaks I and II was significantly shorter ( $P<.05$ ) in the case of red-tailed hawks than for either bald eagles or golden eagles (1.2 ms vs. 1.5 ms vs. 1.4 ms, respectively). In addition, red-tailed hawks exhibited shorter IV-V intervals ( $P<.001$ ) when compared to either eagle species (~1.7 ms vs. 2.9 ms vs. 2.6 ms). These differences most likely reflect differences in the length of conducting segments connecting relevant auditory brain nuclei. Note that we have separated central conduction time (CCT) into individual interpeak intervals in Figure 12 to indicate where in the neural response differences occur.

With regard to the design of alerting/deterrence signals, just as response sensitivity assessments fundamentally inform design considerations, the minimum time required to centrally process acoustic signals influences the time limit governing signal activation timing following the detection of an eagle in the vicinity of a wind turbine. As such, CCT represents a conservative estimate of the minimum amount of time necessary to activate an alerting signal that will permit signal detection by the eagle prior

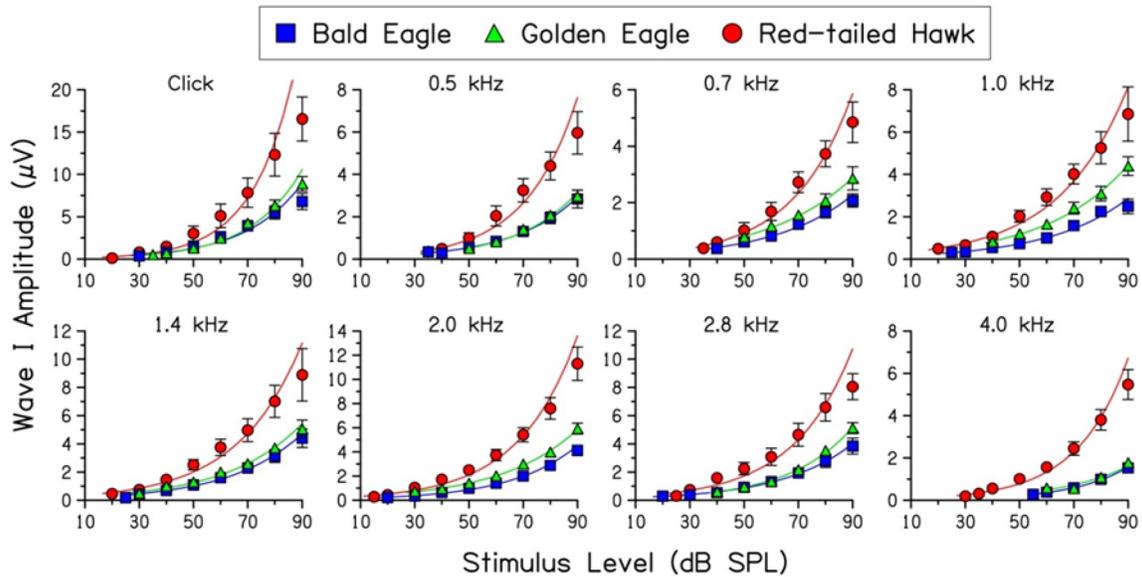


**Figure 12. Interpeak intervals for peaks I to IB, I to II, II to III, III to IV and IV to V are shown for responses to 2 kHz for each of the species studied. Values were averaged across levels and are shown  $\pm 1$  s.d. Significantly shorter IPIs for the red-tailed hawk than either eagle were found for the interval between peaks I and II ( $P<.05$ ) and between peaks IV and V ( $P<.001$ ).**

to a flight-altering motor response that will in turn allow a raptor sufficient time to change its flight path and avoid collision with the turbine.

### *Level-Dependence of Response Amplitudes*

Another relevant supra-threshold response parameter to consider in the context of developing acoustic alerting/deterrence tools is the growth of response amplitude. As illustrated in Figure 13, peak I amplitude increases with increasing level, regardless of species, although response amplitudes are consistently larger in red-tailed hawks than in eagles, particularly at moderate and high stimulus levels. Response amplitudes also grow at a faster pace with increases in level compared to amplitude growth for eagle species. Growth rates are nearly exponential at low and moderate stimulus levels for all species studied.

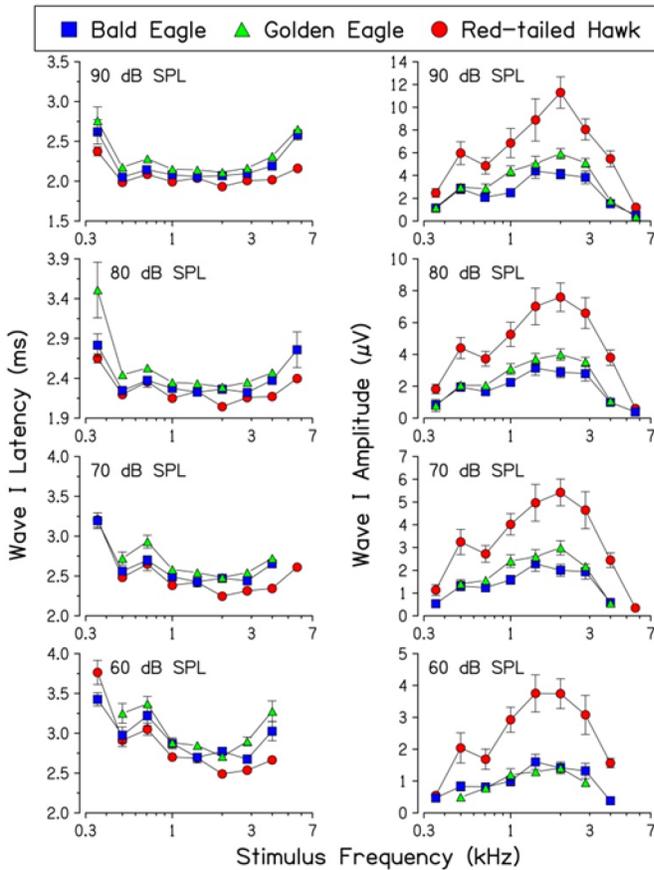


**Figure 13.** Average wave I amplitudes ( $\pm 1$  s.e.m.) are shown as a function of stimulus level for bald eagles (blue squares), golden eagles (green triangles) and red-tailed hawks (red circles) in response to click stimuli and tone bursts ranging from 0.5 kHz to 4.0 kHz. Solid lines represent exponentials fitted to each data set. Note changes in the y-axis scale across panels.

In the context of signal design, broadcast signals should be sufficiently intense to effectively alert target species approaching the sound field of wind farm installations to their presence but simultaneously limit unnecessary contributions to the sound pollution index. When assessed in terms of hearing level (HL), i.e., when referring to level in relation to threshold values, the growth of response amplitude provides a context in which signal designers may consider optimal output levels.

### *Frequency-Dependence of Supra-Threshold Responses*

It is also important in the context of alerting/deterrence technology development to more clearly explore the frequency-dependent nature of supra-threshold responses. In that context, mean response latencies (left column) and amplitudes (right column) are plotted in Figure 14 as a function of stimulus frequency for each raptor species considered. Each row of frames represents a different stimulus level. It is generally reasonable to characterize response latencies as being shortest (i.e., faster response) in the mid-frequency range and slightly longer for responses to both lower and higher frequencies. This pattern tends to be most pronounced at lower stimulus levels while latency values are more or less constant over a wide range of stimulus frequencies at higher stimulus levels.



**Figure 14.** Average ( $\pm 1$  s.d.) wave I latencies (left column) and average ( $\pm 1$  s.e.m.) wave I amplitudes (right column) are plotted as a function of stimulus frequency for levels ranging from 90 dB SPL (top row) to 60 dB SPL (bottom row) for each of the raptor species studied.

When considering average amplitude-frequency relationships, the largest response amplitudes are consistently observed at or near the best frequency, 2 kHz, regardless of level for each raptor. Amplitude values roll off for both lower and higher frequency stimuli, but at a faster rate above best frequency than below creating an asymmetric relationship. Although latencies are fairly similar among the three species across frequency, amplitudes of the red-tailed hawk are clearly larger than those of the eagles regardless of stimulus frequency, most notably in the mid-frequency range.

The essential conclusion drawn from the analysis of response parameter versus stimulus frequency is that 2 kHz, the most sensitive frequency in all three species, elicits the fastest and most robust responses (shortest latency and largest amplitude responses) relative to other stimulus frequencies. This finding may carry high signal engineering relevance in terms of signal efficacy and efficiency.

### Relevant Taxonomic Considerations

In addition to being useful in broad taxonomic and scientific terms, an effort to

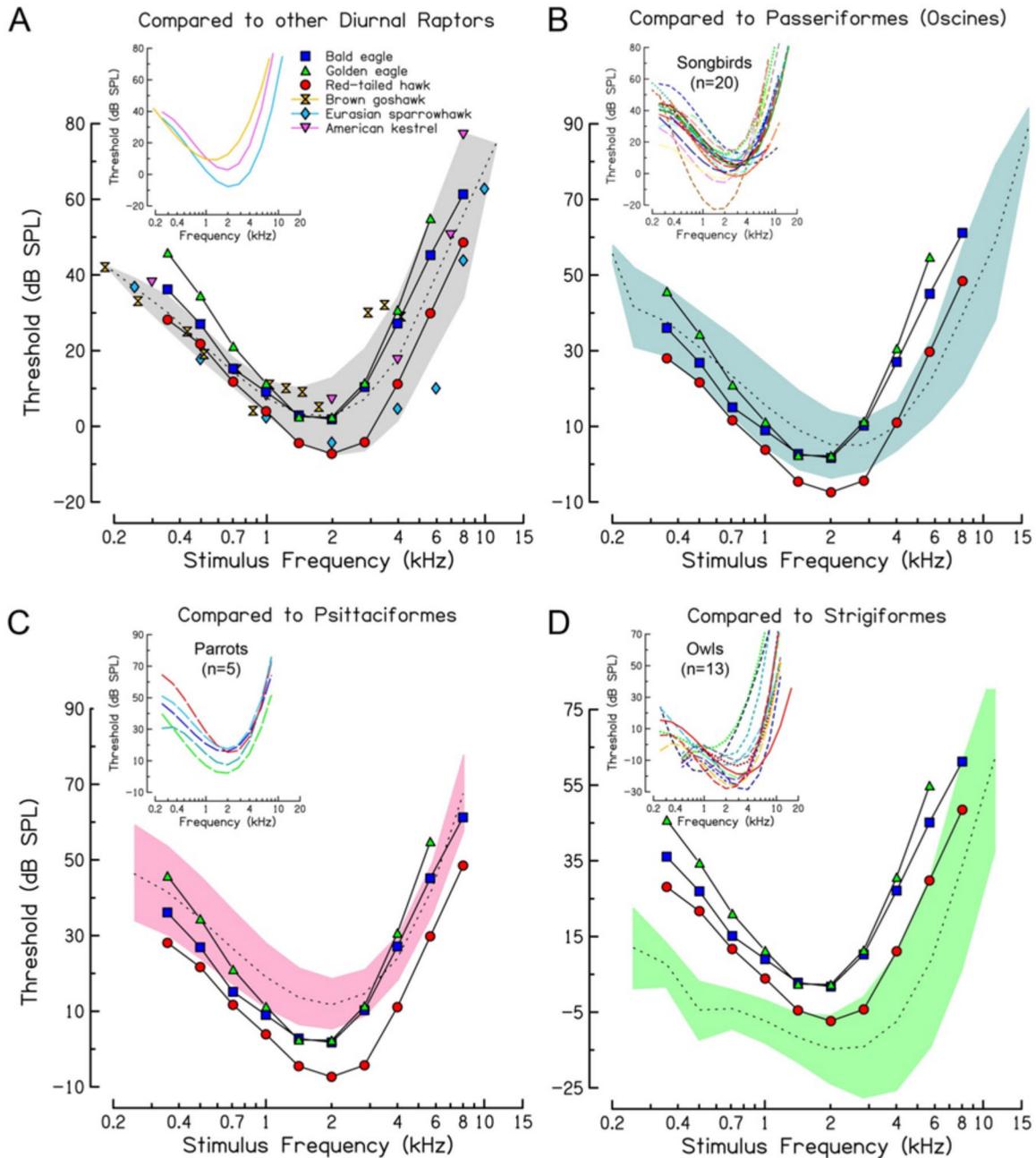
comprehensively consider the sensitivity of avian species to sound takes on substantial relevance in a conservation context when considering the prospective impact of wind turbine collision on an Aves wide basis. To address this concern, we compared the hearing sensitivities of species studied here with average threshold-frequency curves of species belonging to five major taxonomic orders:

- Accipitriformes, the diurnal birds of prey that includes eagles and hawks
- Falconiformes, or falcons, also included in the broad diurnal birds of prey category
- Strigiformes, or owls, classified as nocturnal birds of prey
- Passeriformes, commonly categorized as either perching or songbirds and the largest of the bird orders
- Psittaciformes, or parrots

See Appendix D for a detailed account of the methodology and references used in this comparative analysis.

The threshold-frequency curves of two diurnal species studied previously, including the Eurasian sparrowhawk (*Accipiter nisus*) and the Brown goshawk (*Accipiter fasciatus*), and one falcon, the

American kestrel (*Falco sparverius*) are shown (Klump *et al.*, 1986; Calford, 1988; Trainer, 1946) in Figure 15A. Thresholds reported from these three studies are plotted as symbols in Figure 15A and curves fitted to each data set are shown in the inset. The dotted line and gray shaded area represent the mean  $\pm 1$  s.d., respectively, computed for these three species. Thresholds of bald eagles, golden eagles, and red-



**Figure 15.** Average threshold-frequency curves representing bald eagles (blue squares), golden eagles (green triangles) and red-tailed hawks (red circles) from Figure 8B are compared to other diurnal raptors (A), to Oscine Passeriformes (B), to members of the order Psittaciformes (C), and to members of the order Strigiformes (D). Dotted lines and shaded areas in each large panel represent means  $\pm 1$  s.d., respectively for the other species included in each panel. Fitted curves are shown in the insets for each species. Data for two other Accipitriformes (Brown goshawk and Eurasian sparrowhawk) and from a Falconiformes (American kestrel) are also shown in panel A.

tailed hawks that were adjusted according to the evoked potential to behavioral threshold-frequency correction curve (c.f. Figure 8B) are also shown. Note the similarity of thresholds and frequency ranges representing these species. These raptors generally operate in an auditory space characterized by a frequency band at least four octaves wide and centered on 2 kHz, with an upper frequency limit at 80 dB SPL between 8 and 10 kHz and a lower frequency limit likely extending below 0.2 kHz.

When compared with the average threshold-frequency curve representing Passeriformes (Figure 15B), the eagles and hawk studied here share much, but not all, of their working auditory spaces with the average songbird. Eagles, and to a lesser extent, red-tailed hawks, appear to be slightly less sensitive to high-frequency stimulation than the average songbird, while red-tailed hawks and, to a lesser extent, bald and golden eagles appear to be slightly more sensitive to low-frequency stimulation. These small differences in sensitivity curves are consistent with predictions based on body mass differences given the larger body mass of raptors generally. Likewise, the eagle and hawk sensitivity curves are similar to the average Psittaciformes' sensitivity curve, although the red-tailed hawk appears to be slightly more sensitive across the full-responsive frequency band, and greater sensitivity of the eagles appears to be limited to mid and low frequencies (Figure 15C).

Finally, when compared to Strigiformes (Figure 15D), the mean threshold-frequency curve of owls is on average 20 dB lower than that of the eagles, whereas the average sensitivity curve for red-tailed hawks is higher at low frequencies but similar to that of owls at and above best frequency, albeit in the higher range of owl thresholds. It is useful to note that owls are primarily nocturnal species, and some are well known for specialized hearing. Adaptations include inner ear specializations in the high-frequency base of the owl inner ear that enable some owls to detect an expanded high-frequency range of acoustic events with remarkable sensitivity relative to other avian species (Smith *et al.*, 1985; Fischer *et al.*, 1988; Köppl *et al.*, 1993; Fischer, 1994; Köppl, 1997). In addition to inner ear specializations, an external facial adaptation known as the facial disc, or ruff, collects sound energy and directs it inward toward the external ear aperture, thereby increasing sensitivity by as much as 20 dB (Payne, 1971; Coles and Guppy, 1988). The specialized hearing and associated sensitivity enhancement observed in some owls should be taken into consideration when attempting to develop deterrence technologies with broad avian inclusivity.

Overall, these data suggest that bald and golden eagles and red-tailed hawks essentially navigate the same basic working space as other known and thus far characterized members of the diurnal raptor group, and that birds in general share widely overlapping auditory working spaces.

Results for the bald eagle and red-tailed hawk were published in the *Journal of Comparative Physiology A: Neuroethology, Sensory, Neural, and Behavioral Physiology* in 2019.

### **Turbine Acoustics and Auditory Sensitivities**

Understanding the relationship between wind turbine-generated noise and the auditory sensitivity of raptors of interest considered in this report is key to the development of effective and efficient acoustic alerting/deterrence technologies. We recognize the complex nature of wind turbine sound generation and transmission and acknowledge the need for comprehensive environmental analyses as efforts to engineer and install appropriate sound alerting/deterrence technologies are advanced. The complexity of the challenge facing signal designers is easily understood given the variety of acoustic and topographical environments associated with different siting locations, as well as the variability of noise generation and transmission associated with varying turbine model designs. This degree of complexity will almost

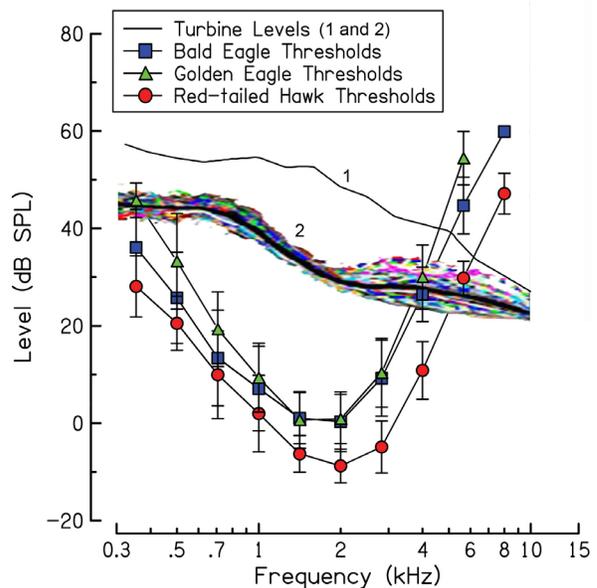
certainly require tailored strategies to meet the acoustic requirements of turbine farm specific installations.

Nonetheless, in Figure 16, we provide an example of the sound pressure level (SPL) versus frequency curve representing the output of a single operational wind turbine (labeled '1'), as well as an example of the output from a wind turbine farm (labeled '2'). Those curves are shown in relation to the average auditory thresholds of raptors studied in this investigation.

Spectrum #1 was acquired at the UMN Eolos Wind Research Field Station, where 36 microphones were evenly positioned in a circular pattern around a 2.5 MW Clipper *Liberty* wind turbine, which has a hub height of 80 m, 3 blades, and rotor diameter of 96 m. Microphones, covered by a primary windscreen, were placed at a radius of 102 m (IEC 61400 standard) from the turbine on 1 m diameter glass plates at ground level. The average power of measurements attained from all 36 microphones over a 270 min time window is shown in 1/3 octave bands spanning the output range. Average wind velocity at hub height was 11.8 m/s and rotor speed was 15.5 rpm, corresponding with the turbine operating at or near its maximum power.

Spectrum #2 is replotted from van den Berg (2006). Data shown here was acquired at the Rhede wind farm in Germany which comprises 17 Enercon E-66 1.8 MW turbines with hub heights of 98 m; each turbine was equipped with three 35-m long blades. These turbines operate at variable speeds that depend on wind velocity. Speeds range from 10 rpm at wind velocities of 2.5 m/s (at hub height) to 22 rpm at wind velocities of 12 m/s and higher. Distance between the microphone and the nearest turbine was 750 m and the microphone was placed 1.5 m above the ground. Average power is shown in 1/3 octave bands as the thick black line and individual measurements are shown as color lines. Average wind velocity at hub height was 14 m/s and rotor speed was 20 rpm at the time of recording.

Note that levels measured 102 m from the single turbine (#1) are nearly 50 dB greater than auditory thresholds in the most sensitive region of the eagle audiograms (i.e., 2 kHz), whereas levels generated by the wind farm (#2) 750 m from the source are nearly 30 dB greater than the most sensitive portion of the audiogram. The important conclusion to take from this exercise is that the noise generated by turbines considered here is capable of masking responses (i.e., capable of interfering with detection) throughout much of the low-frequency range, and well into the high frequency range of eagle hearing. The outcome of this exercise also highlights the need to consider wind-energy installations on a case-by-case basis and to standardize noise assessment protocols to facilitate meaningful facility comparisons. The effective translation of this relationship into meaningful alerting/deterrence technologies will also require additional efforts to understand the masking influence of turbine-generated noise on raptor sound detection.



**Figure 16. Turbine noise levels (measured in 1/3 octave bands) and raptor thresholds are compared across frequency. Threshold values were modified to compensate for temporal integration. See text for a description of turbine noise measurements.**

## Conclusions

Specific findings from this phase of the investigation that are relevant to the design of acoustic alerting/deterrence strategies include the following:

- Bald and golden eagles, as well as red-tailed hawks, are sensitive to a frequency band at least 4 octaves wide and are most sensitive to acoustic events that occur between roughly 0.5 kHz and 4.0 kHz, as measured 20 dB above the lowest threshold.
- All species studied are most sensitive to 2.0 kHz and the estimated behavioral threshold at 2 kHz for eagles is near 0 dB SPL and approximately -7 dB SPL for red-tailed hawks.
- Significant threshold differences were not observed among juveniles and adults within each species.
- Significant threshold differences were not observed between males and females within each species.
- For all species studied, response timing relative to the onset of the signal decreases with increasing stimulus level.
- Response latencies are shortest in the mid-frequency range and responses occur later at both lower and higher frequencies, particularly at lower stimulus levels.
- Response amplitudes grow exponentially with stimulus level for all species.
- For all species, the largest response amplitudes occur at or near the best frequency, 2 kHz, regardless of level. Amplitudes decrease progressively for both lower and higher frequency stimuli but at a faster rate above best frequency than below.
- We conclude that red-tailed hawks are an appropriate surrogate for bald and golden eagles in studies of auditory function based on physiological findings. Red-tailed hawks exhibit similarly shaped threshold-frequency curves, the most sensitive frequency is the same as for eagles, response latencies are similar as those of eagles across both stimulus level and frequency, and response latencies and amplitudes follow the same basic pattern with changes in stimulus level and frequency as those of eagles. Although red-tailed hawk thresholds are slightly lower than those of eagles and response amplitudes tend to be larger, most notably in the mid-frequency range and at moderate to high stimulus levels, hearing in the three species considered here is well matched.
- We note that the behavioral response of the red-tailed hawk was not evaluated directly and therefore we are not able to comment if the behavioral response of the RTH will be representative of an eagle's response to acoustic stimuli, but with respect to hearing ability and auditory function, the species are well matched.
- Turbine noise levels exceed the lowest levels detected by both eagles and red-tailed hawks throughout most of their most sensitive auditory receptive fields (i.e., noise levels produced by turbines are within the audible range of the three raptor species studied here).

In summary, the experimental plan carried out in this investigation is intended to guide engineering efforts to design effective acoustic alerting/deterrence strategies by defining the frequency limits, sensitivities, and input-output properties of bald and golden eagle auditory systems. In addition, based on the comparison of findings in bald and golden eagles, as well as red-tailed hawks, with other avian species, we conclude that the development of effective acoustic alerting/deterrence technologies designed to manage species considered in this report may also protect a wide variety of other avian groups from risks associated with wind turbine collision. While future behavioral tests may reveal species-specific

differences in response to an alerting sound, efforts to address the influence of species dependent behaviors go beyond the scope of this project; one of our chief objectives was to assess hearing in bald and golden eagles, as well as red-tailed hawks, and we found that their audiograms were similar to those of many other avian species.

Note that auditory steady state responses have been acquired, are being analyzed and a manuscript on the topic is planned.

## Phase II – Eagle Vocalizations

### Overview

In the second phase of the study, high quality sound recordings of bald and golden eagle vocalizations were acquired and analyzed in an effort to identify salient call features that may be used in the development of acoustic alerting/deterrence protocols/technologies.

This phase of the investigation required the development of a sound recording system at the UMN Raptor Center, the facility in which vocalizations produced by both permanent residents of the facility (“education birds” that cannot be released into the wild), and bald eagles admitted to the UMN Raptor Center for rehabilitation (“clinic” birds) were acquired. Golden eagle vocalizations analyzed as part of this program of study were acquired from The Macaulay Library at the Cornell Lab of Ornithology (<https://www.macaulay/library.org>).

### Materials and Methods

The data acquisition system used to acquire bald eagle recordings consisted of a Brüel & Kjær 4191 ½” free-field microphone with a frequency response of 3.15 Hz to 40 kHz. The microphone was fitted with a 90 mm wind screen and was connected to a Brüel & Kjær Nexus 2690 amplifier and power supply with built-in high- and low-pass filters. The low-pass filter was set to 100 kHz and had a 40 dB/decade roll-off. The high-pass filter was set to 20 Hz and had an 80 dB/decade roll-off. A National Instruments NI-9239 simultaneous voltage input module was used to capture the acoustic signal. Acoustic pressure measurements were unweighted and recorded at a 50 kHz sampling rate.

Golden eagle calls acquired from The Macaulay Library were recorded using a Nagra III-B recorder. Some calls were recorded using a Sony ECM21 or an Electro-Voice 650 microphone.

### Recording Locations

While golden eagle recordings were acquired from The Macaulay Library, recordings from bald eagles were acquired in two locations:

1. **The Raptor Center pen areas.** Permanent residents were studied in pens outside the facility; the area was surrounded by walls with an open, fenced roof. As a general rule, the distance between test subjects and the recording microphone was on the order of three meters.
2. **The Raptor Center Clinic.** Rehabilitating bald eagles were studied in the clinic itself. The distance between subjects and the recording microphone ranged from approximately 4 m to 18 m.

### Test Subjects

A total of nine bald eagles, five of which were male and 4 female, and a small number of golden eagles were included in the vocalization study. Four of the bald eagles studied were juveniles ranging in age from 2 to 3 years, and five were adults ranging in age from 4 to >27 years. Golden eagles were all adults and included both females and males.

### Data Analyses

Analyses were performed using Raven Pro 1.4 software (Cornell Lab of Ornithology, Ithaca, NY, USA) and Pratt (version 6.0.39) (Paul Boersma and David Weenink).

Calls were categorized and analyzed spectrographically, highlighting the following features:

- **Duration** – the time span of the vocalization measured by visually identifying the time interval in which pressure exceeds the noise floor
- **Fundamental frequency** – lowest frequency in a tonal, harmonic vocalization, measured using an autocorrelation approach
- **Dominant frequency** – the frequency with the highest power in the spectrogram
- **Frequency bandwidth** – the range of frequencies present in the call measured using (1) the interquartile range (IQR), the frequency range containing 50% of the energy in the call, and (2) the frequency range containing 90% of the energy in the call

For calls broadcast as clusters, the number of calls per cluster was tallied and cluster duration was measured.

In addition, the following nonlinear call elements were identified (see Riede *et al.*, 2004 for a detailed discussion of vocal nonlinearity).

- **Biphonation**
- **Subharmonics**
- **Frequency jumps**
- **Deterministic chaos**

Statistical analyses were performed using R (R Core Team, 2018 version 3.5.0). Results of all statistical tests were considered significant when  $P < .05$ .

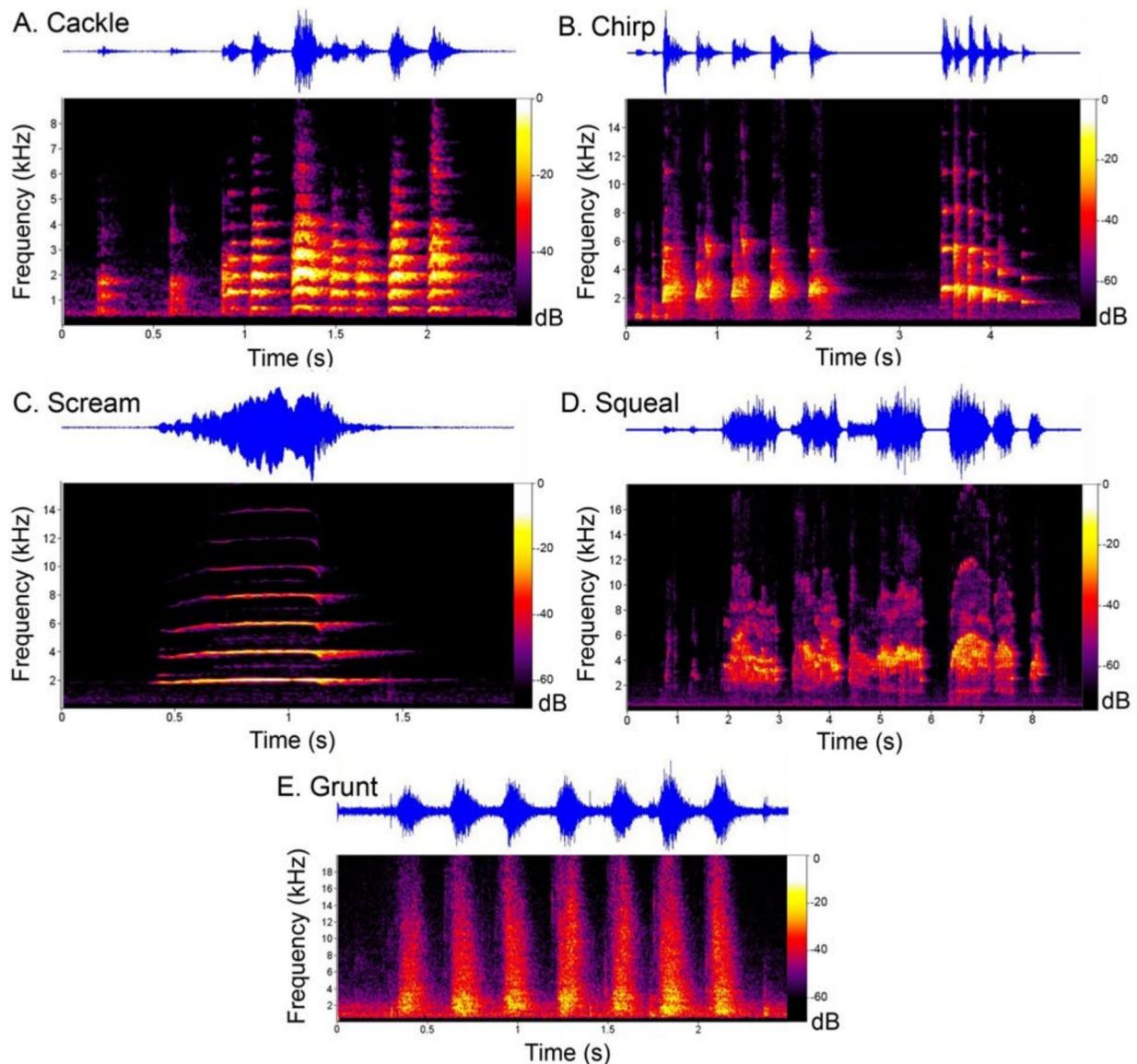
## Results

### Bald Eagle Calls

Three hundred and sixty-two (362) artifact-free bald eagle calls were analyzed in this phase of the investigation. Although a wide range of call categories were initially identified based on subjective impressions, chattering, clucking, snorting, whistling, laughing, and squawking, for example, the following five categories were ultimately recognized as representative of the species' vocal repertoire, and their spectrotemporal and waveform/pressure properties are reviewed below:

- Cackles ( $n=175$ )
- Chirps (88)
- Screams (41)
- Squeals (42)
- Grunts (16).

Examples of each call type are shown spectrographically and temporally in Figure 17.



**Figure 17.** Examples of the five categories of bald eagle calls including a series of cackles (A), a series of chirps (B), a scream (C), a sequence of squeals (D) and a series of grunts (E). For each call, the temporal waveform is shown in the upper panel and the corresponding spectrogram in the lower panel. Note the differences in the time and frequency scales across panels.

As with Phase I studies, this phase of the investigation was motivated by the call for guidance in the development of acoustic alerting/deterrence technologies that might mitigate eagle take rates associated with the operation of wind turbine facilities. The rationale underlying the design of this phase of the research plan is grounded in the view that, along with a solid knowledge of auditory performance, an equally solid knowledge of the acoustic properties of common calls in the eagle’s vocal repertoire will enable the delivery of supplemental guidance in efforts to develop efficient, high performance alerting/deterrence technologies.

This view centers on the assertion that a comprehensive understanding of the spectrotemporal properties, as well as other salient features associated with commonly observed calls in the bald and golden eagle vocal repertoires, might enhance signal design endeavors by adding a dynamic layer to the engineering

initiative. For example, the temporal trajectory of many eagle calls is modulated in both frequency and amplitude domains. They also contain critically important nonlinear features that, together with time varying modulation, may provide acoustic cues with the capacity to affect signal awareness. Likewise, accounting for peaks in spectral power functions of common calls may also prove to enhance the performance of effective alerting signals. Together, a solid understanding of the limits of eagle hearing and a clear recognition of natural, biologically relevant features of aural communication among eagles will, in our view, provide a concrete foundation for the engineering of meaningful protocols.

### Basic Acoustic Properties

Bald eagle calls are, as a rule, distinctly harmonic and broadband in structure. Well-defined harmonic structure and broadband frequency ranges were observed in cackles, chirps, screams and squeals, although grunts, while broadband in nature exhibit little evidence of tonality. The duration of each cackle, chirp and grunt was short, averaging 0.16 to 0.18 s, whereas the durations of screams and squeals were longer (0.6 – 0.7 s). Mean fundamental frequency was lowest for cackles (average of 1.1 kHz), and was higher for chirps, screams and squeals (mean of 2.1-2.9 kHz). As a rule, the dominant or peak frequency tended to be higher than the fundamental frequency and was lower for cackles and grunts (mean of 1.7 kHz) when compared to chirps, screams and squeals (average of 2.7-3.2 kHz). The frequency bandwidth of cackles, chirps, screams and squeals were similar, ranging from 0.5 to 0.9 kHz when considering interquartile [IQR] bandwidth, and 2.1 to 2.4 kHz when considering bandwidth at the 90% level. It is notable that bandwidth was much wider for grunts: 4.5 kHz in IQR terms and 10.9 kHz in terms of the bandwidth at the 90% level. Means and standard deviations for each spectrotemporal characteristic of all call categories are provided in Table 2.

**Table 2. Average Spectrotemporal Characteristics of Bald Eagle Calls ( $\pm 1$  s.d.)**

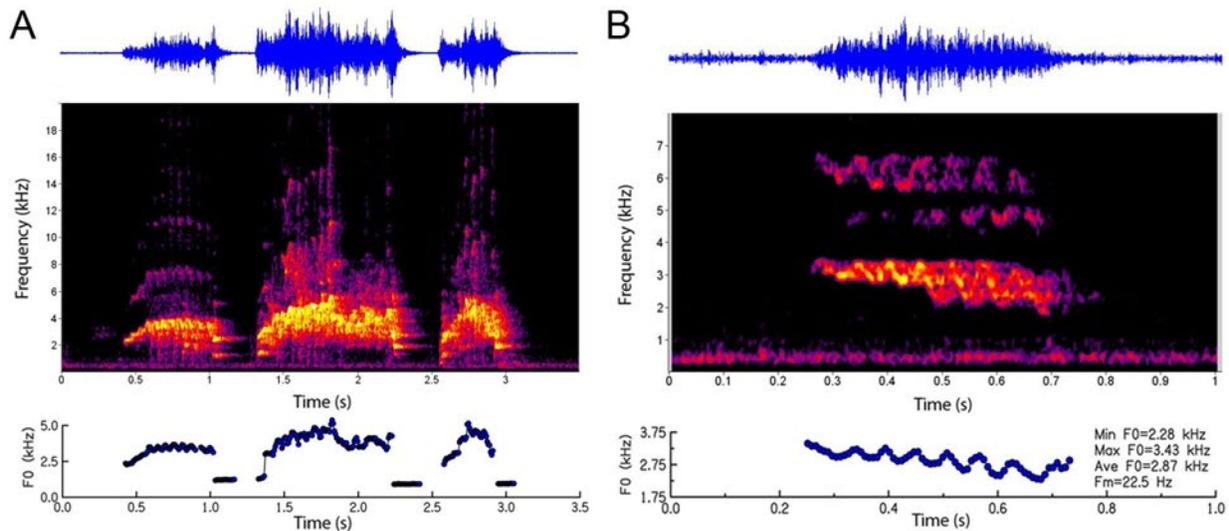
| Parameter                      | Call Category   |                 |                 |                 |                 |
|--------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                                | Cackle          | Chirp           | Grunt           | Scream          | Squeal          |
| Duration (s)                   | 0.18 $\pm$ 0.06 | 0.18 $\pm$ 0.09 | 0.16 $\pm$ 0.02 | 0.71 $\pm$ 0.22 | 0.61 $\pm$ 0.28 |
| Fundamental Frequency (kHz)    | 1.1 $\pm$ 0.4   | 2.8 $\pm$ 0.8   |                 | 2.1 $\pm$ 0.7   | 2.9 $\pm$ 0.9   |
| Dominant Frequency (kHz)       | 1.7 $\pm$ 0.4   | 2.9 $\pm$ 0.9   | 1.7 $\pm$ 0.4   | 2.7 $\pm$ 0.9   | 3.2 $\pm$ 0.8   |
| IQR Bandwidth (kHz)            | 0.7 $\pm$ 0.4   | 0.5 $\pm$ 0.9   | 4.5 $\pm$ 2.2   | 0.9 $\pm$ 0.9   | 0.7 $\pm$ 0.4   |
| 90% Bandwidth (kHz)            | 2.1 $\pm$ 0.8   | 2.3 $\pm$ 1.3   | 10.9 $\pm$ 2.7  | 2.4 $\pm$ 0.9   | 2.4 $\pm$ 1.0   |
| Number of elements per cluster | 6 $\pm$ 3       | 5.6 $\pm$ 2.5   |                 |                 |                 |
| Cluster duration (s)           | 2.14 $\pm$ 2.4  | 1.1 $\pm$ 0.4   |                 |                 |                 |

Cackle and chirp utterances were generally repetitive, occurring in groups of approximately 6 calls per cluster. The average cackle cluster duration was longer and more variable than average chirp clusters (mean of 2 s compared to 1 s, respectively). It should be noted that clusters containing different call types were broadcast on some occasions (e.g., chirps, followed by squeals, followed by more chirping). However, these sequences were not analyzed quantitatively.

## Squealing and Screaming in Bald Eagles

The spectrotemporal and nonlinear character of two calls in the bald eagle vocal repertoire may be of particular interest to prospective alerting/deterrence signal designers given their acoustic quality and complexity. Both squealing and screaming are spectrally complex calls containing an abundance of nonlinear elements often broadcast at high intensities that create a rich sound field with a plethora of potentially meaningful acoustic cues that may be of interest to the sound engineering community.

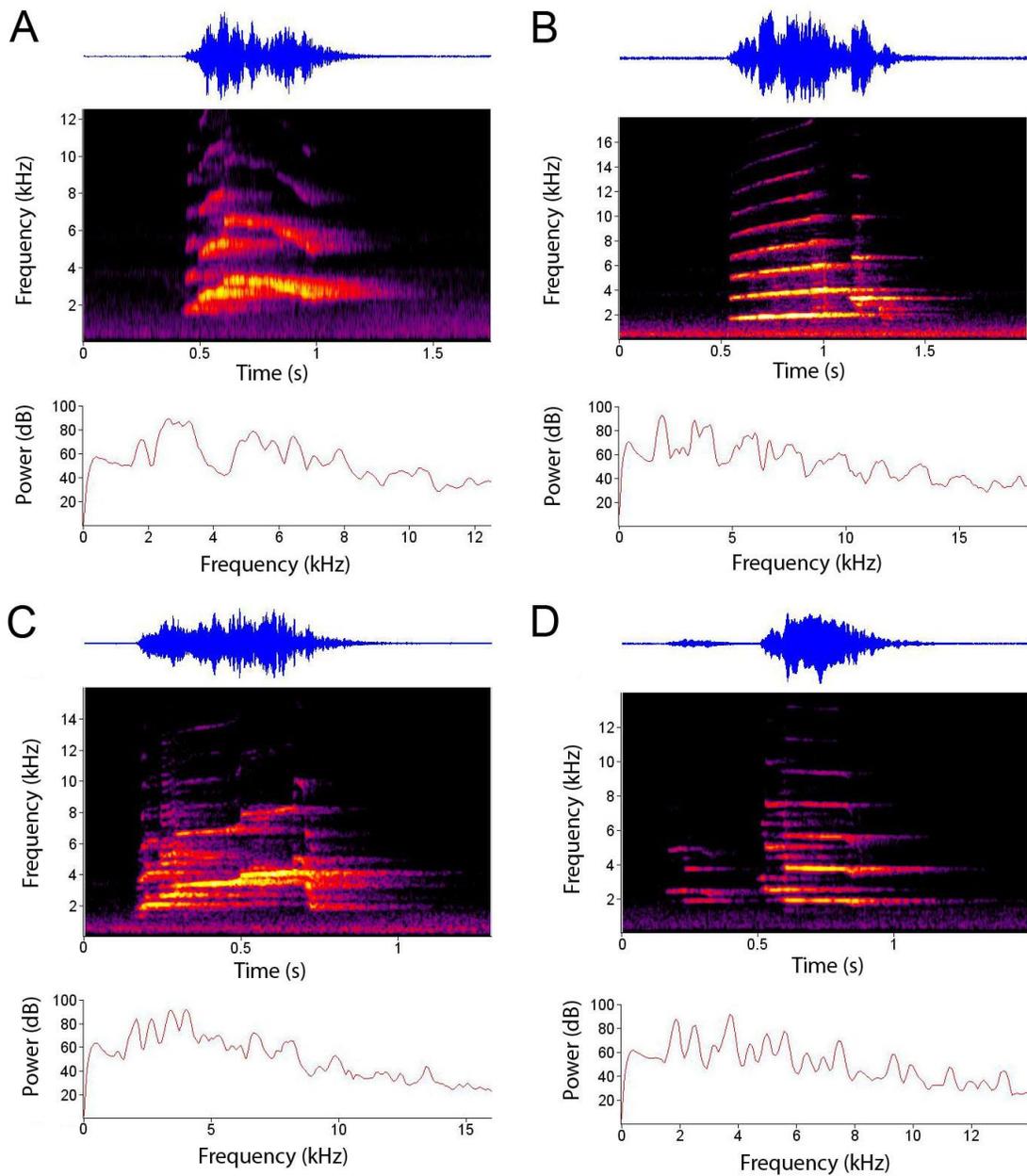
As shown in Figure 18, squeals are particularly interesting from an alerting signal perspective. Pressure waveforms reveal significant amplitude fluctuation in the temporal domain, a feature with potentially relevant properties in a signal habituation context. Squealing may be the richest, most complex call in the



**Figure 18.** Examples of a sequence of squeals (A) and a lower-level squeal on an expanded time scale (B) recorded from bald eagles. Temporal waveforms are located in the upper panels and the corresponding spectrograms in the middle panel. In the lower panels changes in the fundamental frequency (F0), measured using an autocorrelation algorithm are shown over the corresponding time period.

known bald eagle vocal repertoire. The call is typically produced in clusters of three or more bouts varying in duration, and bouts occasionally, if not commonly, coming with other call types like chirps and cackles. The spectral character of squeals is rich and exhibits deterministic chaos-like qualities in some cases, as illustrated spectrographically in the second bout of the sequence shown in Figure 18A. Highly modulated frequency sweeps that typically increase, frequently plateau for varying portions of their overall duty cycle and terminate abruptly in a downward frequency sweep, create a warble-like trill (see Figure 18B) with widely varying acoustic cue content.

The acoustic properties of screaming also offer the signal designer insight into potentially relevant acoustic cues commonly embedded in communication signaling. Screams are harmonically structured calls, as shown in panel C of Figure 17. However, as shown in Figure 19, call complexity is highly variable. In this regard, spectral nonlinearities are a common feature of the scream; 90% of screams exhibit nondeterministic chaos, 80% exhibit biphonation nonlinearity, 66% display subharmonic structure and frequency jumping occurs in 63% of those calls analyzed as part of this project.

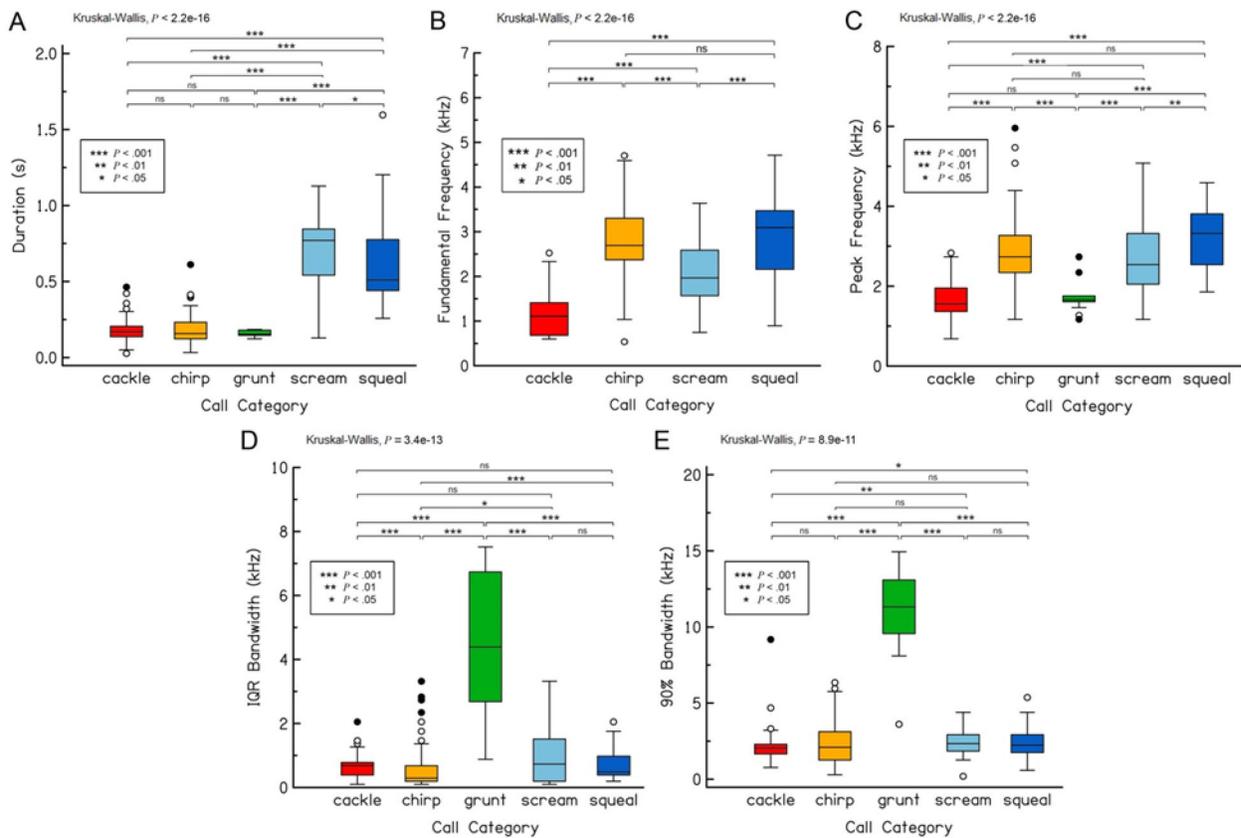


**Figure 19. Four examples of the spectrotemporal characteristics of bald eagle scream variants are shown. In each example, the pressure waveform is shown in the top panel, the spectrogram in the middle panel and the power spectrum in the bottom panel.**

Although the translation of basic findings like those reported here into meaningful, effective and efficient alerting tools will require dedicated acoustic engineering efforts, we are confident that optimal designs based on this body of work will follow, and that the acoustical properties of screams and squeals in particular may serve to facilitate the process.

## Nonparametric Statistical Analyses of Bald Eagle Calls

The spectrotemporal properties of each call type included in this investigation are compared quantitatively in Figure 20, along with tests of statistical significance for differences among call categories. Distributions of each call feature are represented as a box plot with the median shown as the line within the box, and the box itself representing the span from the first to third quartiles (i.e., interquartile range, IQR). The “whiskers” below and above the box represent the minimum and maximum values. Outliers that are 3 or more times the IQR below the first quartile or above the third quartile are represented as filled circles. Suspected outliers, values that do not reach the outlier criteria but are 1.5 or more times the IQR below or above the first or third quartiles, respectively, are represented as unfilled circles.



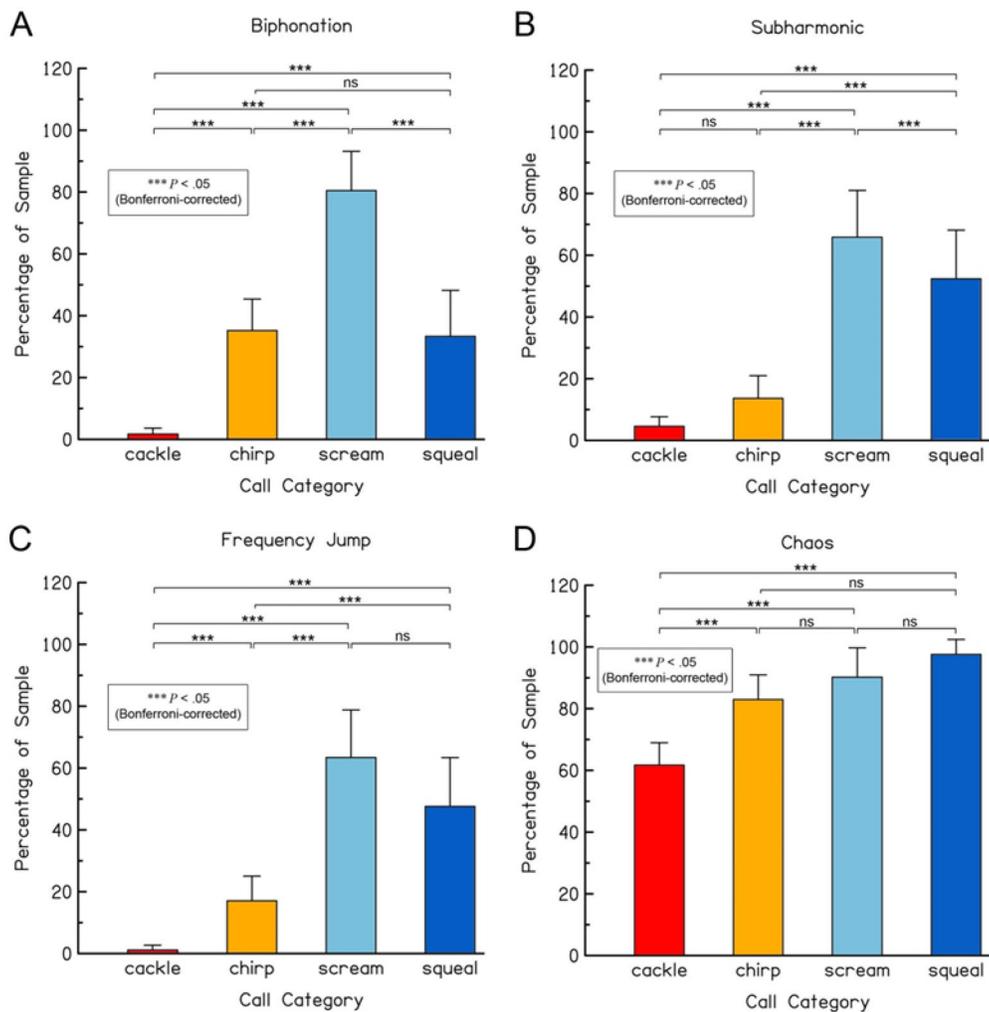
**Figure 20.** Spectrotemporal characteristics of each bald eagle call type are represented as box plots and include call duration (A), fundamental frequency (B), dominant or peak frequency (C), the interquartile (IQR) bandwidth (D) and the bandwidth containing 90% of the call energy (E). Significance differences in the distributions of values among the groups are evident in each plot and as shown by the significant *P*-values derived from the Kruskal-Wallis test shown at the top of each panel. Results of post-hoc analyses are shown as brackets at the top of each frame identifying which calls differ from the other calls and the level of significance is indicated in the symbol key. Non-significant differences are represented as ‘ns.’

To determine the significance of differences in the distributions of values among call categories, a Kruskal-Wallis (non-parametric) test was performed for each parameter; results are shown at the top of each panel in Figure 20 and significant differences among groups were observed for all parameters. Subsequently, comparisons between each pair of vocalization categories were made using the Wilcoxon rank sum test (i.e., Mann-Whitney test) as a post-hoc test and these are shown as pairwise comparisons at

the top of each frame. Significant differences ranged from  $P < .05$  to  $P < .001$  as indicated, and non-significant differences are designated ‘ns.’

### Nonlinear Features in Bald Eagle Calls

Nonlinearities are distinctive attributes in bald eagle vocalizations with potential utility in the design of alerting/deterrence signals. As with most vertebrates, bald eagle vocalizations display a variety of nonlinear features that include biphonation, subharmonic elements, discrete frequency jumping tendencies and deterministic chaos, the latter of which was by far the most commonly observed nonlinear element among all call types being observed in ~75% of all cases. Biphonation was the second most frequently observed nonlinear element, occurring in more than 23% of calls. Subharmonics were observed in 20% and, finally, frequency jumps were observed in 18% of the calls included in this report. Note that grunts were excluded from this analysis.



**Figure 21.** Bar graphs of the percentages of bald eagle calls within each category that display the specified nonlinearity. Percentages of biphonations (A), subharmonics (B), frequency jumps (C) and chaos (D) are shown for each call type (excluding grunts). Results of Bonferroni-corrected, pairwise tests, are shown at the top of each panel. Non-significant differences are indicated by ‘ns.’ Error bars represent 95% confidence intervals.

The presence of each type of nonlinearity was determined for each call, and results tallied for each call type. Figure 21 shows the percentage of calls within each of the call categories that exhibit nonlinear elements, along with the 95% confidence intervals. In addition, the proportion of each nonlinear element was compared across call types and the Bonferroni correction was used to control for multiple comparisons. Results are shown in Figure 21 for each pairwise comparison.

### Comparisons of Bald and Golden Eagle Vocalizations

While similar in spectrographic structure generally, distinctive differences are also clear when comparing spectral and temporal features of bald and golden eagle calls. One significant difference on a call type scale was the failure to identify cackles in the golden eagle vocal repertoire. Likewise, a unique call type described as a golden eagle bark in this report was absent from bald eagle recordings included in this investigation. While other differences are generally less striking, we infer that divergent natural selection pressures led to the evolution of distinctive bald and golden eagle vocal communication signals based on the relatively limited data set available at this point in time.

Examples of temporal waveforms and spectrograms of calls falling into four categories representing the golden eagle vocal repertoire identified in this report are shown in Figure 22; note that the call structure of bald eagle calls can be compared with those of golden eagles by referring to Figure 17.

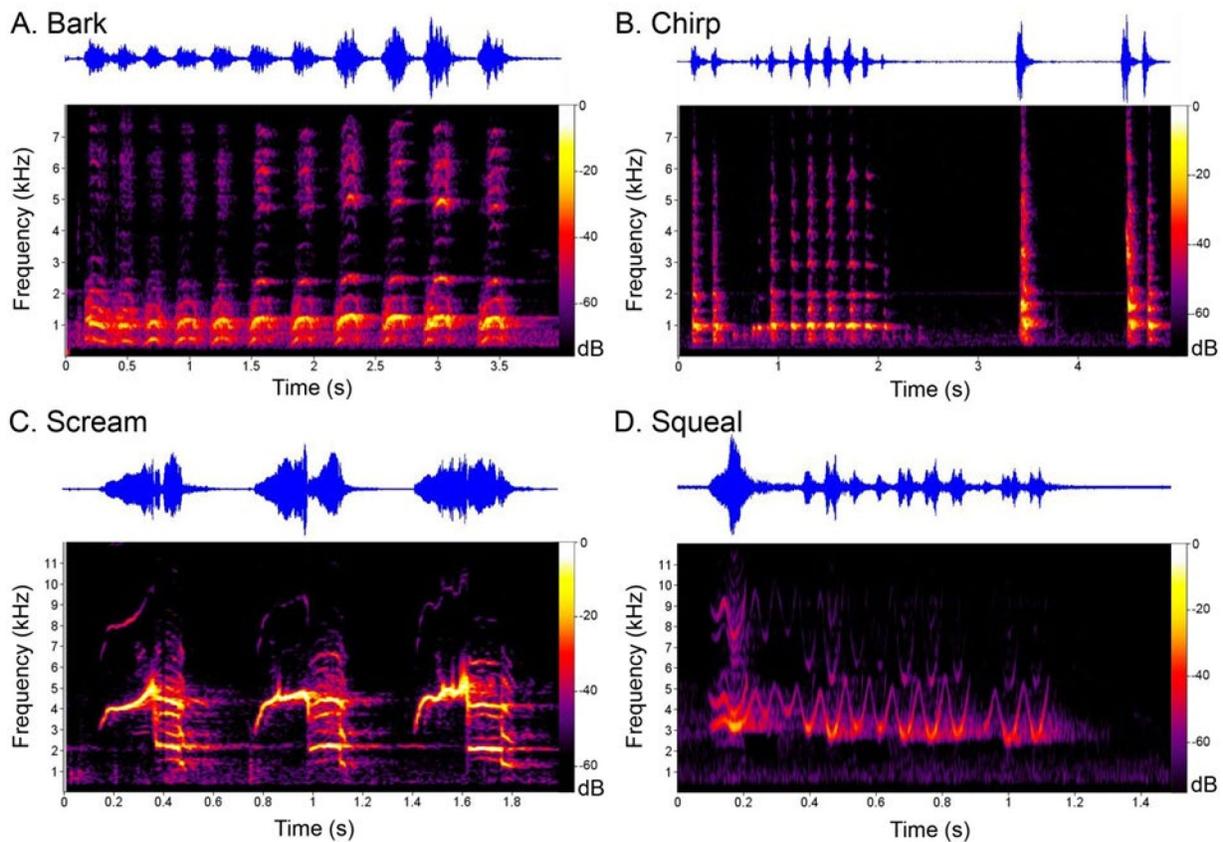


Figure 22. Examples of the four categories of golden eagle calls including a series of barks (A), a series of chirps (B), a sequence of screams (C), and a squeal (D). For each call, the temporal waveform is shown in the upper panel and the corresponding spectrogram in the lower panel. Note the differences in the time and frequency scales across panels.

Three of the golden eagle calls recognized in this report are also represented in the vocal repertoire of bald eagles, the chirp, the scream and the squeal. Generally, golden eagles produce squeals and screams with uniformly shorter durations than bald eagles ( $P < .05$ ), and similar “sounding” calls exhibit distinctively different spectrographic patterns than those of bald eagles. In this regard, note the similarity of the frequency modulated golden eagle squeal (Figure 22D) with those recorded from bald eagles (cf. Figure 18). The resemblance is most striking in the example illustrated in Figure 18B.

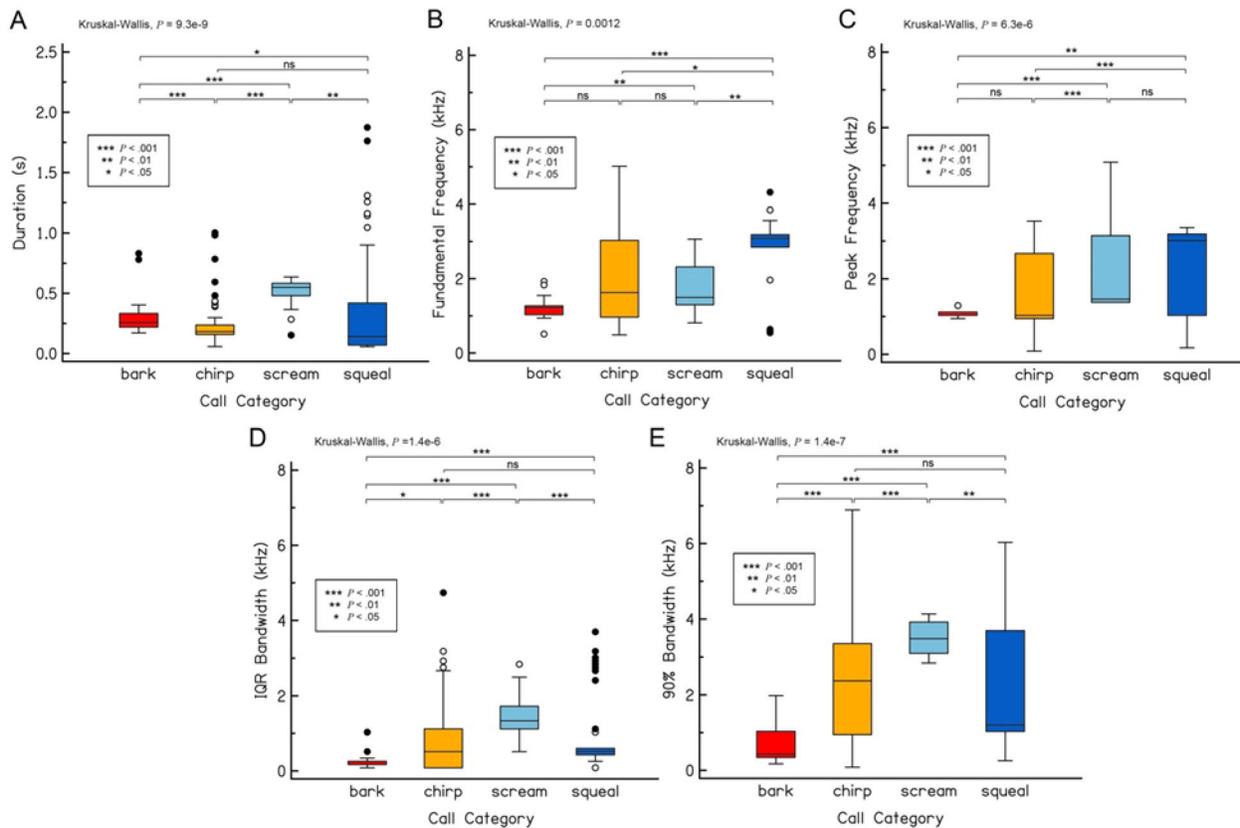
Golden and bald eagle chirps are very similar, although, as with squealing, call durations were more variable when produced by golden eagles. The median fundamental frequencies (F0) of chirps and screams were higher in bald eagles than in golden eagles ( $P < .05$ ), whereas the F0s associated with squeals were closely matched in both species. In the case of peak frequency, significant differences were observed in the cases of chirps and squeals, and again, bald eagle calls exhibited higher frequencies than those of golden eagles. Bandwidth comparisons, measured in terms of IQR and bandwidth at the 90% level, led to the conclusion that the median bandwidth of chirps and squeals are similar, while golden eagle screams exhibit broader bandwidths than those of bald eagles screams ( $P < .05$ ).

Means and standard deviations for each spectrotemporal characteristic of all call categories for the golden eagle are provided in Table 3.

**Table 3. Average Spectrotemporal Characteristics of Golden Eagle Calls ( $\pm 1$  s.d.)**

| Parameter                   | Call Category   |                 |                 |                 |
|-----------------------------|-----------------|-----------------|-----------------|-----------------|
|                             | Bark            | Chirp           | Scream          | Squeal          |
| Duration (s)                | 0.31 $\pm$ 0.17 | 0.22 $\pm$ 0.15 | 0.51 $\pm$ 0.12 | 0.30 $\pm$ 0.50 |
| Fundamental Frequency (kHz) | 1.2 $\pm$ 0.3   | 1.9 $\pm$ 1.2   | 1.8 $\pm$ 0.7   | 2.6 $\pm$ 1.1   |
| Dominant Frequency (kHz)    | 1.1 $\pm$ 0.1   | 1.5 $\pm$ 1.0   | 2.5 $\pm$ 1.4   | 2.2 $\pm$ 1.2   |
| IQR Bandwidth (kHz)         | 0.24 $\pm$ 0.23 | 0.83 $\pm$ 0.92 | 1.46 $\pm$ 0.62 | 0.95 $\pm$ 1.02 |
| 90% Bandwidth (kHz)         | 0.69 $\pm$ 0.52 | 2.37 $\pm$ 1.66 | 3.49 $\pm$ 0.44 | 2.22 $\pm$ 1.70 |

The spectrotemporal properties of each call type analyzed for golden eagles included in this investigation are compared quantitatively in Figure 23, along with tests of statistical significance for differences among call categories.



**Figure 23.** Spectrotemporal characteristics of each golden eagle call type are represented as box plots and include call duration (A), fundamental frequency (B), dominant or peak frequency (C), the interquartile (IQR) bandwidth (D) and the bandwidth containing 90% of the call energy (E). Significance differences in the distributions of values among the groups are shown by the significant *P*-values derived from the Kruskal-Wallis test shown at the top of each panel. Results of post-hoc analyses are shown as brackets at the top of each frame identifying which calls differ from the other calls and the level of significance is indicated in the symbol key. Non-significant differences are represented as ‘ns.’

Results (*P*-values) of non-parametric statistical analyses (Kruskal-Wallis tests) of spectrotemporal parameter comparisons between bald and golden eagle calls considered in this investigation are shown in Table 4.

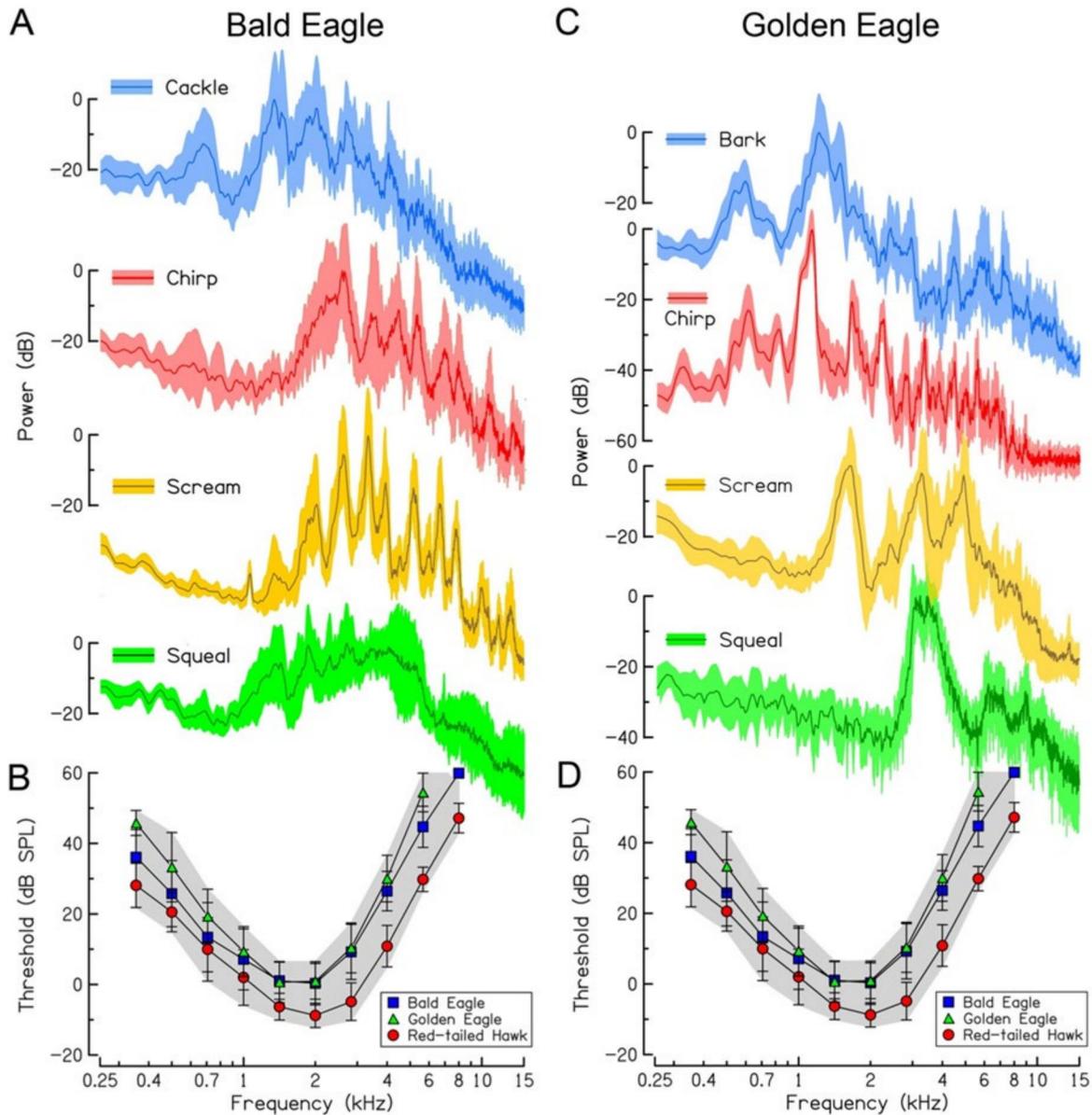
**Table 4.** Kruskal-Wallis *P*-values of Call Parameter Comparisons between Bald Eagle and Golden Eagle Calls

| Parameter                   | Call         |             |              |
|-----------------------------|--------------|-------------|--------------|
|                             | Chirp        | Scream      | Squeal       |
| Duration (s)                | 0.02018 *    | 0.00075 *** | 0.000015 *** |
| Fundamental Frequency (kHz) | 2.39E-07 *** | 0.04924 *   | 0.2665 ns    |
| Dominant Frequency (kHz)    | 3.16E-14 *** | 0.08717 ns  | 0.000549 *** |
| IQR Bandwidth (kHz)         | 0.5272 ns    | 0.01243 *   | 0.6679 ns    |
| 90% Bandwidth (kHz)         | 0.9596 ns    | 9.56E-06 ** | 0.06171 ns   |

Abbreviations: ns, non-significant; \*, *P* < .05; \*\*\*, *P* < .001.

## Power Spectra Considerations

Comparing the average power spectra of the four most common calls observed in bald and golden eagles with corresponding threshold-frequency curves, as shown in Figure 24, demonstrates that the acoustic energy of calls considered in this report tend to fall into overlapping, but different frequency ranges of the acoustic sensitivity curve.



**Figure 24.** Average power spectra  $\pm 1$  s.d. of four categories of bald eagle (A) and golden eagle (C) vocalizations are shown as color lines and shaded regions, respectively. For comparison, auditory thresholds of bald and golden eagles, as well as red-tailed hawks as a function of frequency are replotted in panels B and D. Note that the same frequency scale is used for both power spectra and auditory thresholds.

Solid color lines and shaded areas in panels A and C of the figure represent means  $\pm 1$  s.d. for each call type. The bulk of acoustic energy associated with the major vocalization categories representing bald eagles (panel A) and golden eagles (panel C) fall clearly, and predictably, within the responsive frequency

band (panels B and D). Although relatively broadband in nature, chirps, screams and squeals produced by bald eagles (Figure 24A) contain energy that tends to concentrate in the middle and higher frequency range of acoustic sensitivity, while the acoustic energy of cackles is centered on best frequency and is more evenly distributed within the band of greatest sensitivity (panel B).

Like bald eagles, golden eagle calls (Figure 24C) are also relatively broadband in nature, although screams contain energy that tends to concentrate in the middle and higher frequency range of acoustic sensitivity, while the acoustic energy of barks and chirps is centered near best frequency and is more evenly distributed within the band of greatest sensitivity (panel D). Squeals are uniquely narrowband and high frequency in nature.

## Conclusions

Specific findings from this phase of the investigation that may be relevant to the design of acoustic alerting/deterrence strategies include the following:

- The lowest frequency of bald eagle calls ranges from approximately 500 Hz to 4700 Hz, with an average of ~2000 Hz.
- The dominant or peak frequency of bald eagle calls ranges from approximately 1200 Hz to 6000 Hz, with an average of ~2300 Hz.
- Interquartile (IQR) bandwidth of bald eagle vocalizations ranges from approximately 100 Hz to 7500 Hz, with an average of ~830 Hz, and the 90% bandwidth ranges from 200 Hz to 15 kHz, with an average of ~2600 Hz. If calls in the ‘grunt’ category are excluded, the maximum IQR and 90% bandwidths are ~3300 Hz and ~9200 Hz, with averages of ~660 Hz and ~2200 Hz, respectively.
- Individual bald eagle vocalizations range in duration from ~25 ms to ~1.1 s, with an average of ~0.3 s, although call types with the shortest durations are often repetitive.
- Most bald eagle calls exhibit one or more nonlinear characteristics (~79%), with chaos dominating (75% of calls), followed by biphonation (24%), subharmonics (20%) and frequency jumps (18%). Over 30% of calls are characterized by two or more nonlinear features.
- Although the repertoires of both bald and golden eagles include calls categorized as chirps, screams and squeals, differences in power spectra between the species are evident. While “cackling” is a common call type in the case of bald eagles but was not observed in golden eagles, “barking” is common among golden, but not bald eagles.
- Statistically significant differences are observed in the spectrotemporal parameters of bald and golden eagle calls categorized as chirps, screams and squeals.
- Bald and golden eagle calls contain energy that span their audible frequency range, but different calls tend to concentrate energy in different regions of the receptive frequency range.

In summary, in concert with findings from Phase I, vocalization acoustics findings are intended to guide engineering efforts to design effective acoustic alerting/deterrence strategies by supplementing information regarding the basic auditory performance attributes of bald and golden eagles. Calls in the vocal repertoires of both species are enriched by widely varying frequency and amplitude modulation patterns, as well as a host of nonlinear elements that enhance call complexity. While auditory performance traits may layout the essential acoustic foundation of effective alerting signals, the dynamic,

cue rich domain of vocalization acoustics may encourage signal designers to increase signal complexity to enhance the alerting quality of effective and efficient deterrence signals. In addition, the frequency distribution associated with the power spectra of at least a subset of calls may provide additional guidance in the effort to design meaningful acoustic alerting/deterrence technologies.

## Phase III – Behavioral Responses of Bald Eagles to Acoustic Signals

### Overview

In this phase of the investigation, the behavioral responses of bald eagles to a broad range of natural and synthetic acoustic stimuli were analyzed as a first and preliminary step in the effort to translate findings from Phase I and II into a behavioral platform that can be used in more formal controlled behavioral studies.

### Test Subjects

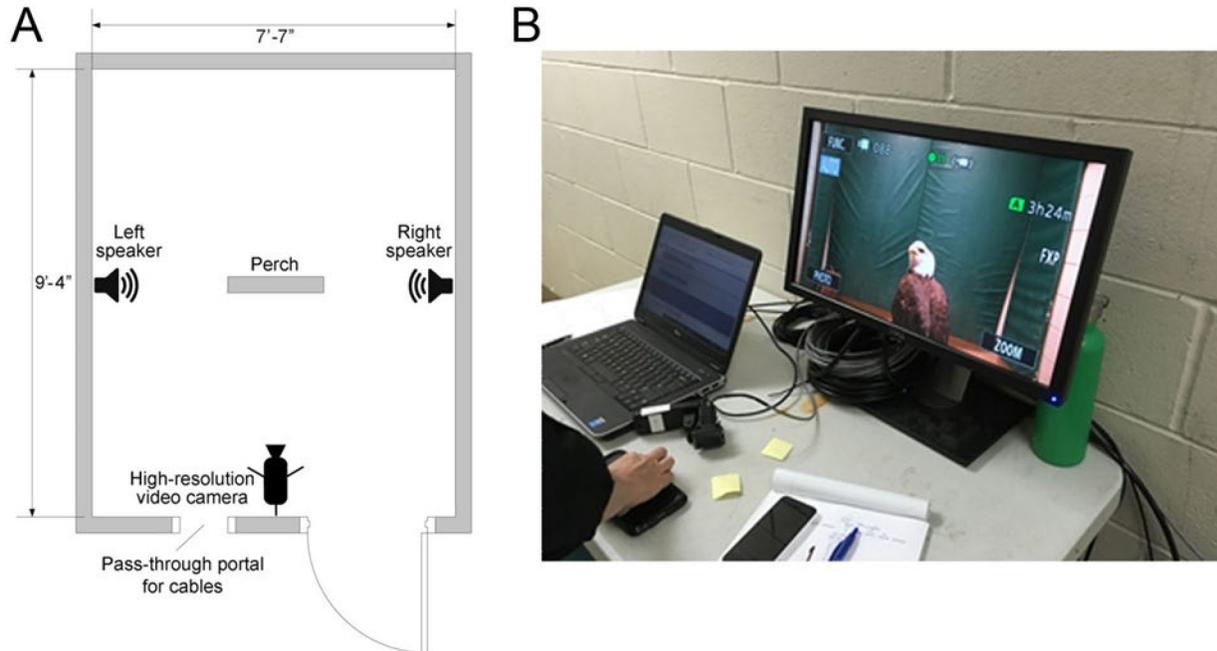
Three adult bald eagles participated in this phase of the investigation.

- Bald Eagle 1
  - Permanent resident (unable to be released back into the wild)
  - 20 years old
  - Admitted to the facility during hatch year with a wing fracture
  - Female
- Bald Eagle 2
  - Temporary resident (will be released after full rehabilitation)
  - > 5 years old
  - Admitted to the facility with a wing injury
  - Male
- Bald Eagle 3
  - Permanent resident
  - 21 years old
  - Admitted to the facility in hatch year with elbow luxation
  - Male

### Experimental Setup

Behavioral tests were conducted in a small (approximately 70 square feet floor area), acoustically dampened room. A perch was positioned on the floor in the center of the room and wall-mounted speakers were placed at 90-degree angles relative to the perch at the approximate height of the subject's head when perched. A high-resolution video camera was positioned directly in front of the perch. A schematic of the setup is shown in Figure 25A.

Investigators viewed live video feed from a remote location outside the study space and controlled the delivery of randomly selected signals to one of the two wall-mounted speakers when the eagle was stationary, while acquiring audio/video recordings of the test subject (Figure 25B).



**Figure 25. A. Schematic of the room and equipment layout used for behavioral testing, indicating locations of the perch, speakers and video camera. B. Photograph of the remote location used for viewing the live video feed, delivering audio signals, and acquiring data.**

## Acoustic Stimuli

Ten stimulus types were selected for inclusion in preliminary behavioral tests. Four were natural calls consisting of an adult bald eagle scream, and adult bald eagle squeal, an eaglet grunt (recorded in the course of this project), and the sound of mobbing crows obtained from the internet. In addition, six synthetic stimuli were included:

- **Pure tone:** a 2 kHz tone, with 10 ms rise/fall times
- **White noise:** white noise bandlimited between 0.3 and 4 kHz, with 10 ms rise/fall times
- **AM:** a sinusoidal amplitude modulated (SAM, AM) signal, with a carrier frequency ( $F_c$ ) of 2 kHz, a modulation rate ( $F_m$ ) of 12.5 Hz and 100% modulation depth
- **FM:** a sinusoidal frequency modulated (SFM, FM) signal, with an  $F_c$  of 2 kHz, an  $F_m$  of 12.5 Hz, and frequency range ( $\Delta f$ , Hz) of  $200 \cdot F_c$ , and 10 ms rise/fall times, identified as “FM”
- **AM Complex:** a SAM harmonic complex, with  $F_c=0.5, 1, 2$  and 4 kHz and  $F_m$  of 12.5 Hz
- **FM Complex:** a SFM harmonic complex, with  $F_c=0.5, 1, 2$  and 4 kHz,  $F_m$  of 12.5 Hz,  $\Delta f$  of  $200 \cdot F_c$ , and 10 ms rise/fall times.

The rationale underlying the selection of bald eagle vocalizations as test stimuli is predicated on an *a priori* assumption that members of a species will be responsive (i.e., will pay attention) to calls within the vocal repertoire of the species at large. Second, the mobbing crow call was selected because of its alerting and agonistic character and an *a priori* assumption that presumably well-recognized combative signals may elicit the attention of the target/receiver. The eaglet grunt was selected based on the *a priori* assumption that signals produced by immature members of the species may effectively capture the attention of adult birds.

Synthetic stimuli selection was based on both the hearing attributes and vocalization characteristics reported in Phase I and II of this investigation. From a synthetic design perspective, two broad sound categories were of interest in the context of signal complexity: narrowband and broadband stimuli. An equally important question focused on whether, and to what degree, habituation was observed in response to signals of varying complexity.

Consequently, an array of signal types ranging from simple to complex was incorporated into the investigation. The simplest signal type was a pure tone, the spectral content of which is nominally contained in a single frequency. On the other end of the complexity scale, bandlimited white noise containing energy spanning the responsive frequency range, as well as the peak vocal output range, was included in the investigation. Between these extremes, a variety of signals with increasing and varying temporal and spectral complexity were considered in both narrowband and broadband realms.

More specifically, both tones and multi-tonal harmonic complexes were modulated in either the amplitude or frequency domains. The tonal frequency and the carrier frequencies for AM and FM signals were set to 2 kHz, the frequency to which eagles were most sensitive and is representative of the average fundamental and dominant frequencies of eagle vocalizations generally. For AM and FM harmonic complexes, the carrier frequencies were chosen in octave steps and ranged from 0.5 to 4 kHz, again based on the most sensitive, responsive frequency range and the range of the dominant vocalization frequencies.

Temporal waveforms and spectrograms of each signal used in this phase of the investigation are shown in Figure 26. All stimuli were approximately 1.04 s in duration and were delivered at 80 dB SPL. Signals were calibrated at the level of the eagle's head prior to each recording session, and stimuli were delivered in random order to each subject.

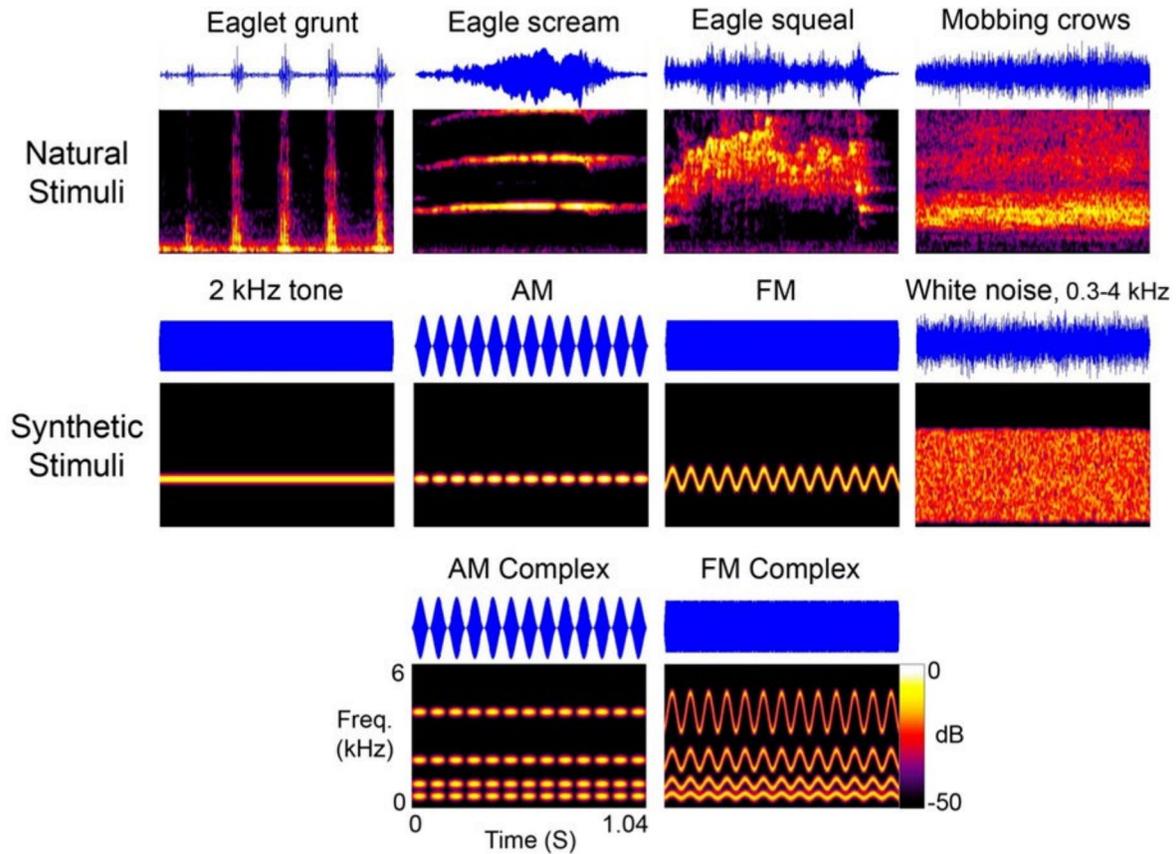


Figure 26. Temporal waveforms and spectrograms are shown for each of the stimuli used for behavioral testing. Natural stimuli are shown in the upper row and the six synthetic stimuli are shown in the center and bottom rows. The annotations of the x- and y-axes shown in the lower left panel apply to all spectrograms, as do the z-axis annotations shown in the lower right panel.

## Data Acquisition

A trained handler positioned subjects on the perch and study sessions were initiated after the subject acclimated to the test space and remained stationary on the perch for a minimum of 10 seconds. Stimuli were delivered to a randomly selected speaker when the subject's head was positioned no more than ~30 degrees from the midline.

Stimuli were delivered in signal sets containing ten trials of an identical stimulus type. Trials were identified by the investigator as invalid if subjects moved just prior to, or in concert with the delivery of the stimulus and an additional trial was added to the regimen under these conditions. A total of ten signal sets, all containing ten trials, were presented in any given recording session. The protocol is schematized in Figure 27. Each video recording contained the results of all trials presented for one signal set.

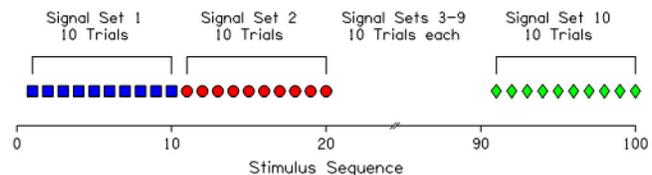
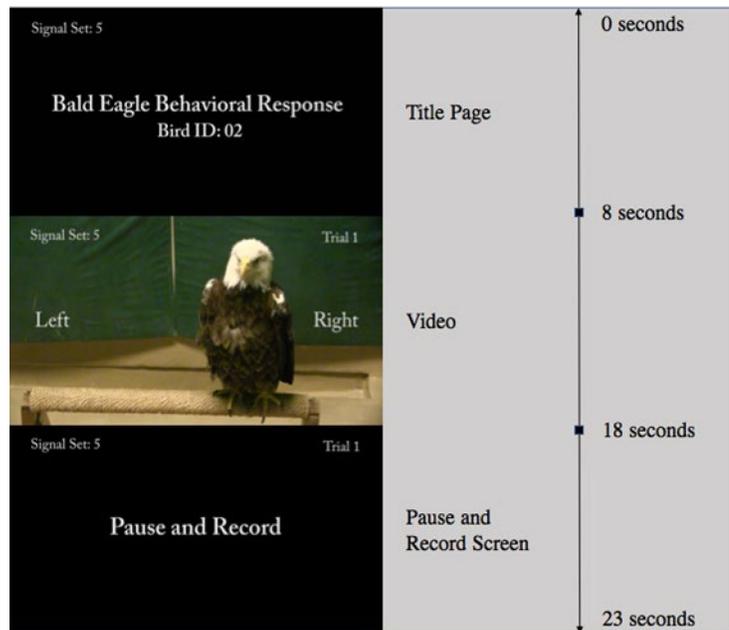


Figure 27. Schematic illustration of the sequence of stimuli delivered including the different stimulus types (signal sets) and trials for each stimulus type. Different stimulus types are represented by different symbols

## Video Editing

Audiovisual recordings were trimmed and edited to produce uniform assessment records consisting of three segments, a title segment lasting approximately 8 seconds that displayed bird ID and signal set number, a ten second video recording segment that launches 5 seconds prior to stimulus delivery, and a pause and record segment during which assessors complete the Response Evaluation Form (Appendix E). Assessor bias was avoided by replacing the actual sound file containing the delivered sound with a generic tone and video clips were labeled with the text “Left” and “Right” for consistent identification of speakers from the perspective of the viewer. The signal set number was displayed in the top left corner of the title, behavioral video, and the pause and record segments. The trial number was displayed in the upper right corner of the behavioral video, and the pause and record segment (see Figure 28).



**Figure 28.** Example “timeline” of an edited video showing the three primary segments of video clips. Top: title page with Bird ID and signal set indicated that is shown for 8 s; Middle: 10-s video recording of bird that begins 5 s prior to stimulus delivery, and includes signal set number, trial number, and left right indicators; Bottom: pause and record frame, with the signal set and trial number indicated that is shown for 5 s.

## Data Analyses

An adaptation of the Observer Based Psychoacoustic Procedure (OBPP) was used to assess stimulus driven behavioral responses. This approach has been used successfully to study hearing in human infants (Werner and Gillenwater, 1990) and preliminary findings here indicate that the approach can be successfully adapted to investigate eagles in a behavioral context.

Nine independent judges volunteered to review videos. A subset of judges were Raptor Center volunteers, and some were students enrolled in an animal bioacoustics course at the University. One judge was a scientist who studies hearing and another was a chemist. Each reviewer received written behavioral assessment instructions, a written description of the video format, and a Response Evaluation Form (see Appendix E). Judges were instructed to focus on the bird for the full 10-s video clip and to enter their observations/scores onto the Form when the ‘Pause and Record’ screen was displayed.

Judges were further instructed to indicate if the bird responded to the stimulus, or not, and to judge the strength of the response when detected; selection options included in the Response Evaluation Form were *weak*, *intermediate*, or *strong*. Additional suggested descriptors of the response included the selection options *head turning towards the left or the right*, *head tilt*, *minor startle*, *major startle*, *quieting effect*, *mouth opening*, or *other*. Acoustic startle responses are reflexive musculoskeletal reactions to unanticipated stimuli and the magnitude of the movement depends on many factors, including the number of central neurons within the reflexive pathway that are activated. The most evident manifestation of ‘minor’ startles was a lurching head movement, and a ‘major’ startle was a marked full body reflexive

movement to the stimulus. Judges were instructed to select all applicable responses and to provide additional response descriptions not included in the Response Evaluation Form when observed. Data reported by each judge were entered into a Microsoft Excel spreadsheet, sorted and analyzed. Note that judges were blind to both stimulus type and the speaker to which the signal was delivered.

## Results

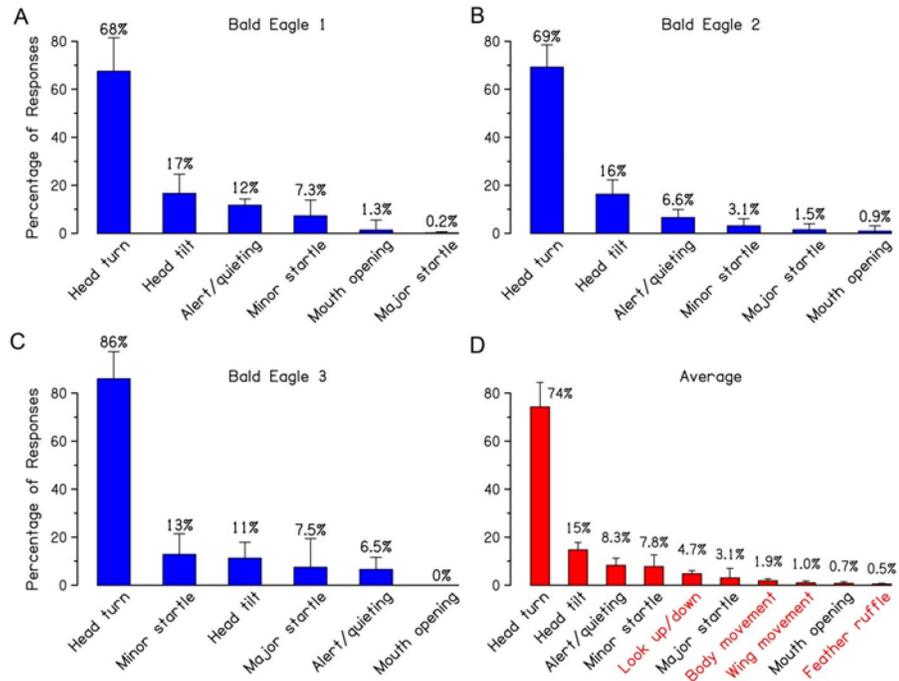
### Bald Eagle Reaction to Acoustic Stimuli

The results of studies conducted during this phase of the project have a direct bearing on the ultimate goal of engineering effective acoustic alerting/deterrence technologies. The questions addressed in this section center on what sound types produce responses in bald eagles, do subjects respond more frequently to certain classes of sound and, perhaps most important, what signals, or combination of signals, if any, create a condition of nonhabituation in which attention to signals are not extinguished over time.

### Response Behaviors

As pointed out above, a jury of judges was asked to select which, if any, of the behaviors listed in the Response Evaluation Form were observed in responsive subjects. As shown for individual eagles in Figure 29A-C, head turning was by far the most common behavioral response to acoustic stimulation, being reported in between 68-86% of responses across all signal sets and trials; an average of 74% of all responses were identified as a head turn. The next most common response behavior was head tilting, but this reaction was observed on average only 15% of the time. The frequency with which other behavioral responses was reported dropped off rapidly on average, as illustrated in Figure 29D in which average percentages of responses representing specific behaviors to all stimulus types, and including four additional behaviors recognized by jurors (identified in red font) are shown.

Findings reported here indicate, as anticipated, that bald eagles respond to detectable sound events commonly and, as a rule, respond to all signal types included in this study. Evidence

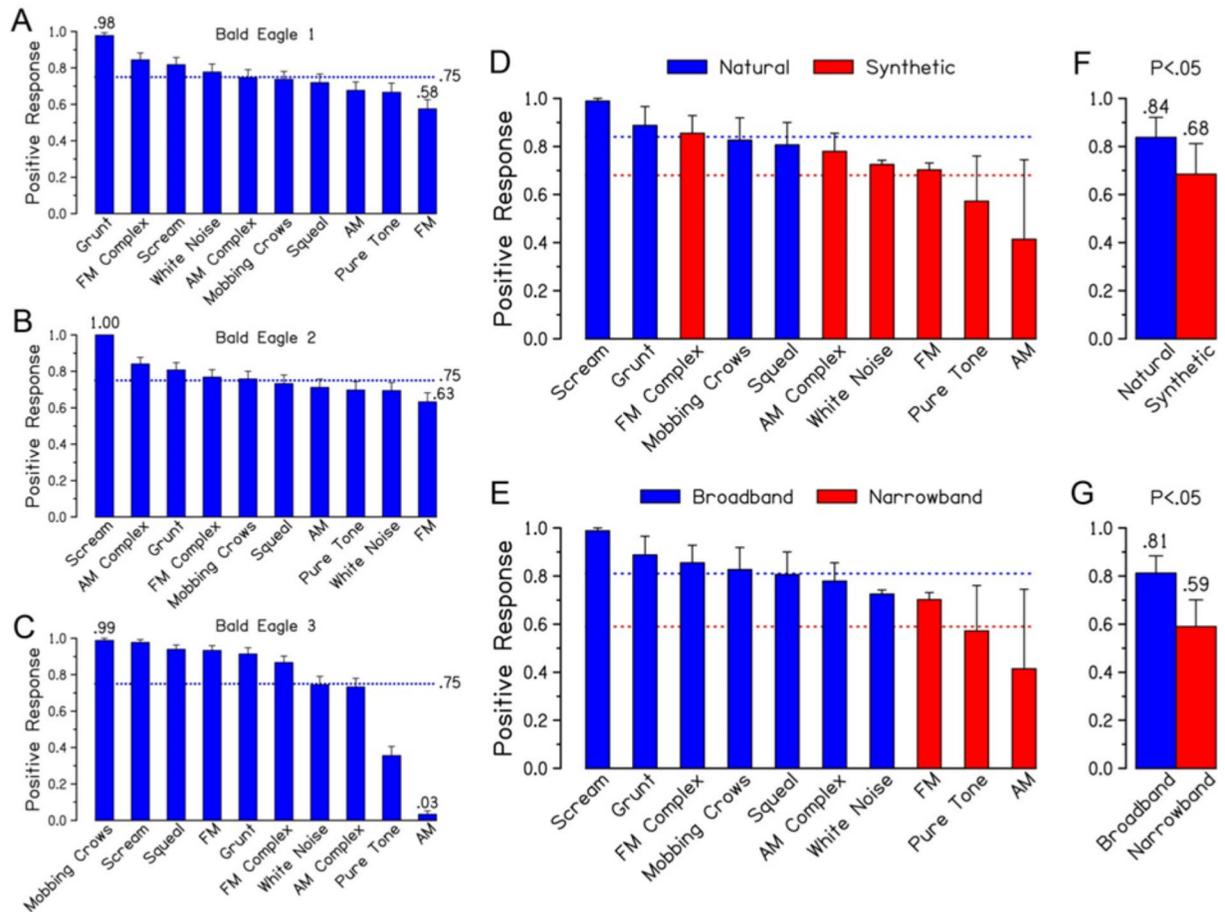


**Figure 29. Percentages of responses to stimuli are shown for each response behavior listed on observations sheets for individual eagles (A-C) and for the average (D). Bars are ranked from high to low, and data are pooled across both signal sets and trials. Additional response behaviors identified by judges are included in panel D indicated by the annotations in red font.**

supporting this conclusion is shown in Figure 30A-C in which proportions of trials in which positive responses were observed are rank ordered from most to least preferred signal type for each subject.

Although subjects responded to stimuli, regardless of signal type, on average 75% of the time (blue dashed lines in Fig. 30A-C), responses to natural stimuli were observed on average 84% of the time (blue dotted line in Fig. 30D), compared with 68% when synthetic signals were presented (red dotted lines in Figure 30D).

Subjects also responded to broadband signals more frequently than to narrowband signals, simple tonal signals for example. Responses to broadband signals were observed 81% of the time, compared with 59% of narrowband signal types included in the investigation, as shown in Figure 30E and 30G. Differences are significant at the  $P < .05$  level.



**Figure 30.** Proportions of positive responses for each stimulus type (pooled across trials) are shown for each bird in panels A-C, along with standard error bars. Averages across birds are shown in D and E, which are identical except for the color-coding; in D bars representing natural and synthetic stimuli are blue and red, respectively. In E bars are colored based on whether the stimulus was broadband (blue) or narrowband (red). Averages of positive responses for all natural and all synthetic stimuli are shown in F and for broadband vs. narrowband stimuli in G. Bars in each histogram are rank-ordered from high to low. Means across signal sets are shown as dotted lines in A-E. Differences in F-G are significant at  $P < .05$ .

### Habituation to Repeated Stimuli

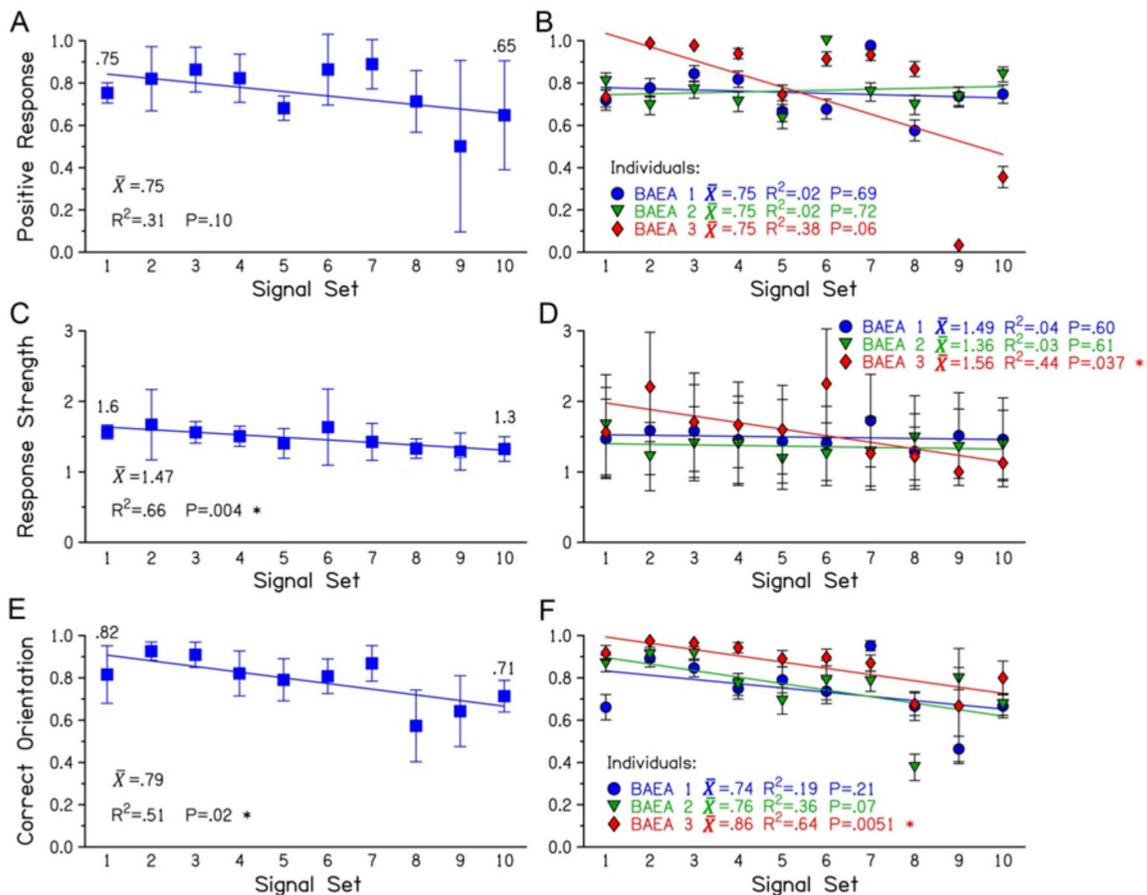
Signal habituation is generally recognized as a concern when designing acoustic alerting/deterrence technologies, and informed consideration of the relevance of habituation requires comprehensive

consideration of wide-ranging parameters that characterize flight behaviors near wind farm environments. In this section, we take the first step to address this concern by considering the extent to which bald eagles habituate to each signal type studied in this investigation under tightly controlled in-house conditions.

Habituation tendencies were assessed by considering three parameters:

- The percentage of “positive responses” observed;
- “Response strength” determined by converting the categorical data “*weak*”, “*intermediate*” and “*strong*,” as identified in the Response Evaluation Form, into numeric values of 1, 2 and 3, respectively;
- “Correct orientation” determined by calculating the percentage of head turns toward the speaker broadcasting the trial.

Habituation was examined first by comparing each response measure from the first signal set delivered to the tenth signal set, as shown in Figure 31, for both averages across birds (left column) and for individuals (right column). Proportions of trials in which positive responses were observed are shown in the top row, response strength in the middle row, and correct head orientations in the bottom row. Significant individual or average differences were not observed across signal sets, including Bald Eagle



**Figure 31.** Three measures of responsiveness are shown from the first to tenth signal sets in the form of across eagle averages (A, C, E) and for individual birds (B, D, F). Data from individuals are averaged across trials within each signal set and least-squares linear regressions for each bird are shown as the lines in B, D and F. Means across signal sets, along with regression coefficients and *P* values are shown for both averages and individuals. BAEA, bald eagle.

#3 whose performance degraded markedly near the end of the test sequence, as shown for signal sets 9 and 10 in Figure 31B. While differences in the strength of response reported for Bald Eagles #1 and #2 were not significant across signal sets, Eagle #3's performance decreased significantly, influencing the average, which also decreased significantly from 1.6 to 1.3 as a consequence. Finally, head turning towards the correct speaker tended to decrease for all subjects, but was significant only for Eagle #3, as well as the overall average across signal sets ( $P < .05$ ).

The order of signals, corresponding to signal set number, delivered to each eagle is indicated in Table 5.

**Table 5. Sequence of Stimuli Delivered to each Bald Eagle Corresponding to Signal Set Number**

| Signal set | Bald Eagle ID |               |               |
|------------|---------------|---------------|---------------|
|            | 1             | 2             | 3             |
| 1          | Squeal        | Grunt         | AM complex    |
| 2          | White noise   | White noise   | Mobbing crows |
| 3          | FM complex    | FM complex    | Scream        |
| 4          | Scream        | AM            | Squeal        |
| 5          | Pure tone     | FM            | White noise   |
| 6          | AM            | Scream        | Grunt         |
| 7          | Grunt         | Mobbing crows | FM            |
| 8          | FM            | Pure tone     | FM complex    |
| 9          | Mobbing crows | Squeal        | AM            |
| 10         | AM complex    | AM complex    | Pure tone     |

Habituation was also considered across repeated stimulus trials when response performance (i.e., percentage of positive responses) was collapsed across signal type. Results are shown in Figure 32 using the same format as in Figure 31. The top row represents the proportion of stimuli in which positive responses averaged across subjects were observed (panel A) and for individual eagles (panel B), and significant decreases in positive responses were observed across trial number for two individuals (Eagles 1 and 3), as well as for the average. Note, however that positive responses were observed for a majority of the signals delivered on the tenth trial, i.e., 66% of trials. Likewise, response strength decreased significantly for two individuals (Eagles 2 and 3), as did the average across trials. Finally, although accuracy trended downward when considering head orientation behavior, significant habituation was limited to Eagle 3 and the average data set, which remained at 60% correct for the final trials across signal sets.

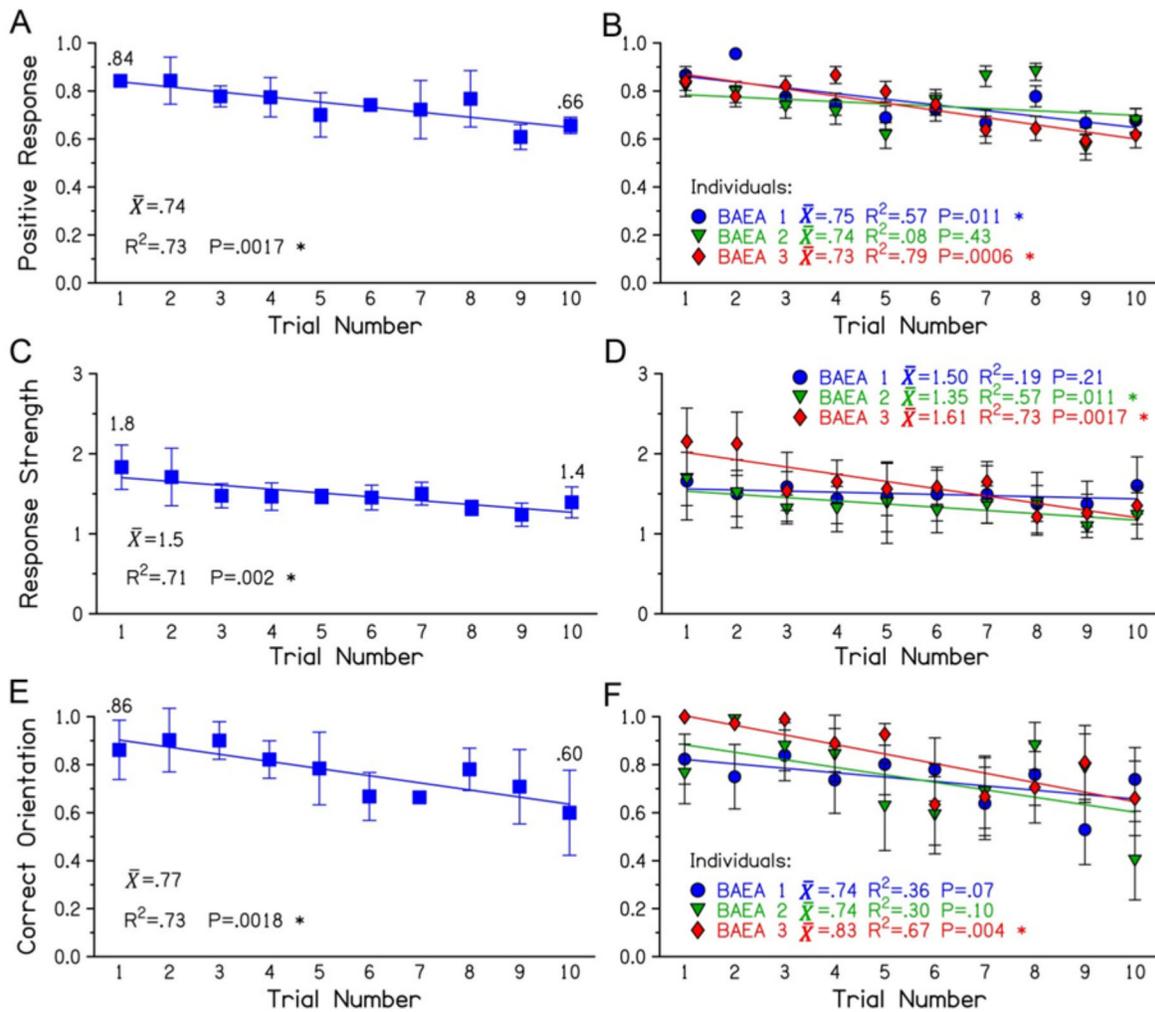
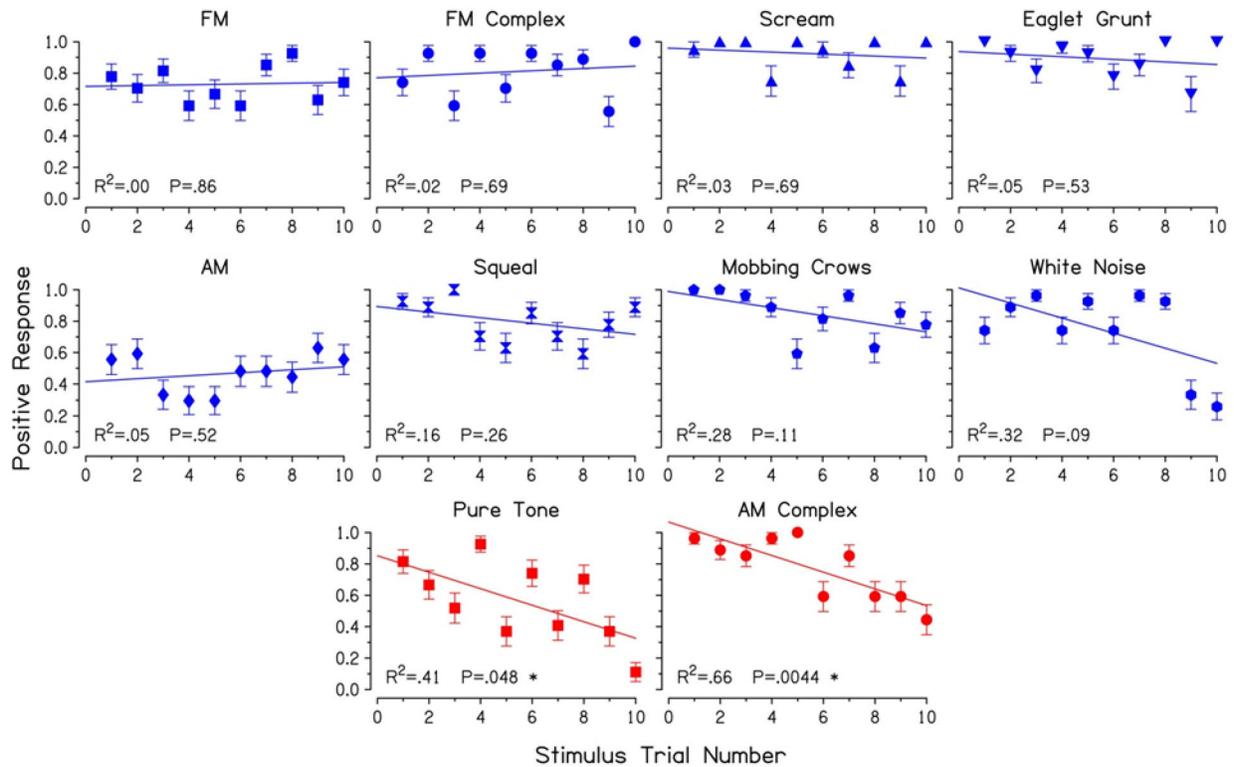


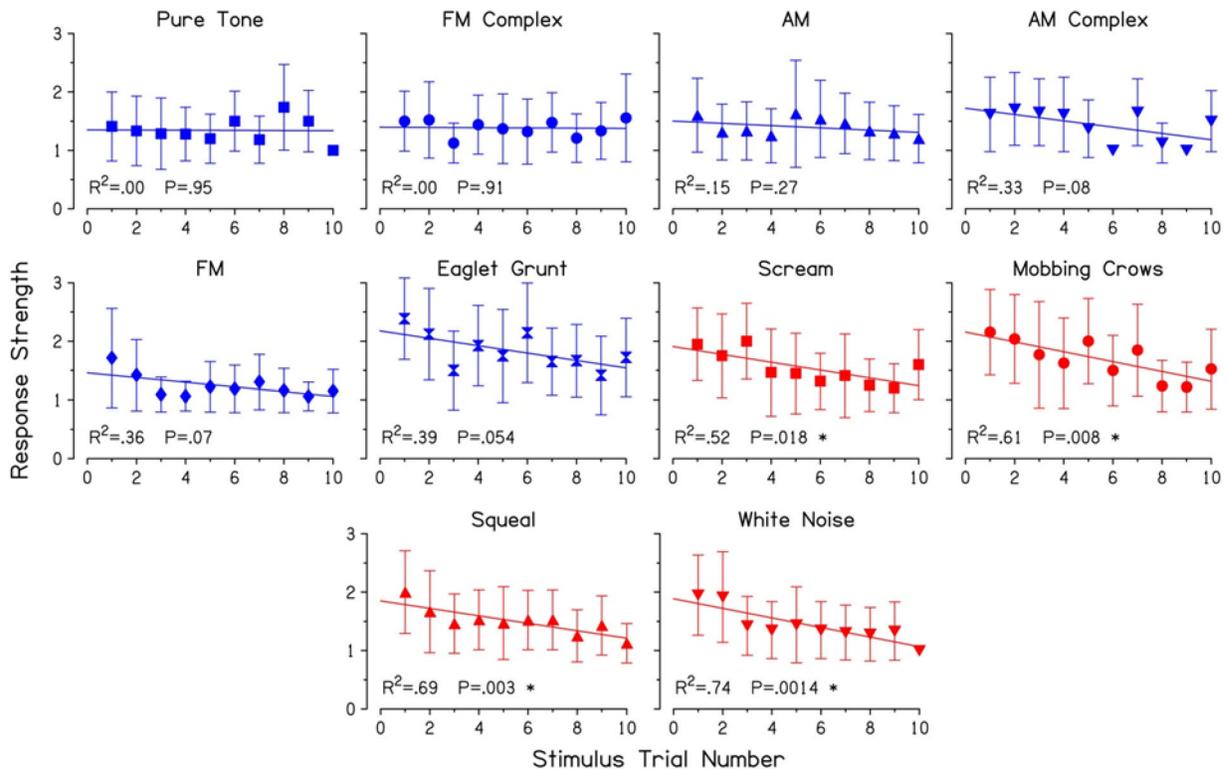
Figure 32. Three measures of responsiveness are shown from the first through tenth trials in the form of across eagle averages (A, C, E) and for individual birds (B, D, F). Data from individuals are averaged across signal sets and least-squares linear regressions for each bird are shown as the lines in B, D and F. Means across trials, along with regression coefficients and P values are shown for both averages and individuals. BAEA, bald eagle.

In addition, to determine if changes in the proportion of positive responses across trial number were affected by different stimulus types, averages across eagles were plotted for each stimulus type as a function of trial number. The results are shown in Figure 33. Regressions to data represented for the eight stimuli plotted in the top two rows (shown in blue symbols and regressions) were not statistically significant. In contrast, the regression lines shown to the stimuli in the bottom row (pure tone and AM complex) showed a statistically significant drop in positive responses across trials.



**Figure 33.** Positive response proportions, averaged across subjects, are plotted as a function of trial number for each stimulus type presented and panels are arranged in order from high to low  $P$ -values. Least squares linear regressions are shown as lines and regression coefficients, along with  $P$ -values, are shown in each panel. No statistically significant differences were found for the stimuli plotted in the top two rows (blue) ( $P > .05$ ); however, the regressions shown in the bottom row (red symbols and lines) are statistically significant ( $P < .05$ ).

A similar analysis was performed for response strength to determine if that variable was influenced by signal type across trial numbers. Results are shown in Figure 34, which has a similar layout to that shown in Figure 33. Regressions to response strength vs. trial number for six of the stimuli (shown in blue) showed no significant change across trials ( $P > .05$ ), whereas regressions to four of the stimuli (red symbols and lines) were statistically significant ( $P < .05$ ).



**Figure 34.** Response strength, averaged across subjects, is plotted as a function of trial number for each stimulus type presented, and panels are arranged in order from high to low P-value. Least squares linear regressions are shown as lines and regression coefficients and P-values are shown in each panel. Statistically significant differences were not observed for the stimuli shown in the top row or for the two left panels shown in the middle row (blue) ( $P > .05$ ); however, the regressions shown in the right two panels of the middle row and those in the bottom row (red symbols and lines) are statistically significant ( $P < .05$ ).

### Influence of Test Subject Age on Behavioral Responsivity

Two of the three subjects tested as part of this pilot investigation were over 20 years of age. Eagles live 20 to 30 years in the wild, and individual bald eagles are known to live significantly longer in captivity. The older bald eagles enrolled in this preliminary study have lived in captivity for much of their lives. Although the overall sample size in this study is too small to determine the influence of age on behavioral responses, auditory performance in the older birds could not be differentiated from the younger subject. In addition, it is safe to assume that age is not a significant factor in hearing the test signals used for behavioral testing because birds continuously regenerate inner ear sensory cells throughout their lifespan; this ability protects birds from presbycusis, or age related hearing loss, and suggests that the age difference noted here is likely to be inconsequential as it relates to the detection of acoustic signals. As our team moves this preliminary study into a fully controlled investigation, our plan was, and continues to

be, to study wild (and younger) bald eagles that have been fully rehabilitated at the Raptor Center, although it may be interesting to incorporate age as an independent variable in future studies.

## Conclusions

Specific findings from this phase of the investigation include the following:

- The most common behavioral response to stimuli is head orientation toward the signal source; eagles oriented towards the correct speaker on average 79% of the time across all stimuli.
- Eagles responded to stimuli 74% of the time, on average, approaching 100% for stimuli to which individuals are most responsive.
- Eagles were more responsive to natural stimuli when compared to synthetic stimuli (84% vs. 68% positive responses).
- Eagles were more responsive to wideband stimuli when compared to narrowband stimuli (81% vs. 59% positive responses).
- The percentage of positive responses remained constant across stimulus sets and across stimulus trials for the majority of stimuli. However, habituation was observed across trials in response to tonal stimulation and the complex AM stimulus, as well as the overall average.
- Response strength remained constant across stimulus sets in two eagles, but decreased for one individual, as did the average response; strength of response remained constant across stimulus trials for 6 stimuli, but decreased for 4 stimuli (screams, mobbing crow calls, squeals and white noise), as did the overall average.
- The percentage of correct head orientations toward the speaker delivering the stimulus did not change across stimulus sets for 2 eagles, but performance in one eagle declined, along with the overall average; percentages did not change with trial number for 2 eagles, but did for 1 eagle and the overall average.

Results reported here are promising, but more data from a larger sample size are clearly required in the effort to draw firm conclusions. In addition to testing a broader range of stimuli, future studies might consider interleaving both trials and stimulus types to prevent or reduce habituation. Finally, testing the efficacy of potential acoustic deterrent signals in more natural environments will be necessary in the drive to develop and install effective deterrent technologies.

## Acknowledgments

The authors would like to acknowledge the essential contributions from Drs. Michelle Willette and Dana Franzen-Klein, Drew Bickford, Andrew Byrne, Jamie Clark, and The Raptor Center volunteers. In addition, the authors are deeply grateful to Mr. Bill Voelker and Troy from Sia, The Comanche Nation Ethno-Ornithological Initiative for not only permitting us to study the golden eagles that they care for, but for also the warm hospitality demonstrated during our visit to their center. This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Wind Energy - Eagle Impact Minimization Technologies and Field Testing Opportunities, Award Number DE-EE0007881.

Portions of the work described above have been presented or published previously (Marr *et al.*, 2018; McGee *et al.*, 2019a, 2019b, 2019c; Ponder *et al.*, 2018; Walsh *et al.*, 2018a, 2018b, 2018c).

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Walsh EJ, Nelson P, Ponder JB, Milliren C, Feist C, Marr J, Redig P, McGee J (2018c) The auditory attributes of Golden Eagles: Do Golden (*Aquila chrysaetos*) and Bald Eagles (*Haliaeetus leucocephalus*) share the same auditory space? *J Acoust Soc Am* 144(3, Pt. 2 of 2):1792.

Werner LA, Gillenwater JM (1990) Pure-tone sensitivity of 2- to 5-week-old infants. *Infant Behav Dev* 13:355-375.

## Publications

McGee, J., Nelson, P.B., Ponder, J.B., Marr, J., Redig, P. and Walsh, E.J. (2019). Auditory performance in bald eagles and red-tailed hawks: A comparative study of hearing in diurnal raptors. *J. Comp. Physiol. A: Neuroethology, Sensory, Neural, and Behavioral Physiology*, 205(6):793-811, DOI: 10.1007/s00359-019-01367-9.

The online version of the article (<https://doi.org/10.1007/s00359-019-01367-9>) contains electronic supplemental material.

<https://link.springer.com/article/10.1007/s00359-019-01367-9>

<https://experts.umn.edu/en/publications/auditory-performance-in-bald-eagles-and-red-tailed-hawks-a-compar>

## Abstracts, Conference Proceedings and Presentations

*Behavioral responses suggest bald eagles closely monitor their immediate acoustic environment.*

Presented at the 177<sup>th</sup> Meeting of the Acoustical Society of America (Vol. 145, Issue 3, Pt. 2 of 2, p. 1806) in Louisville, Kentucky, held May 13-17, 2019.

<https://acousticalsociety.org/program-of-177th-meeting/>

<https://asa.scitation.org/doi/abs/10.1121/1.5101615>

*Navigating the acoustic territory of Bald (Haliaeetus leucocephalus) and Golden (Aquila chrysaetos) eagles.* Presented at the 42<sup>nd</sup> Meeting of the Association for Research in Otolaryngology (Vol. 42, 622) in Baltimore, Maryland, held Feb. 9-13, 2019.

[https://cdn.ymaws.com/www.aro.org/resource/resmgr/mwm2019/aro\\_2019\\_updated\\_program\\_fin.pdf](https://cdn.ymaws.com/www.aro.org/resource/resmgr/mwm2019/aro_2019_updated_program_fin.pdf)

*Research into the auditory attributes, vocal characteristics, and behavioral response of eagles to acoustic stimuli.* Presented at the 12<sup>th</sup> National Wind Coordinating Collaborative (NWCC) Wind Wildlife Research Meeting in Minneapolis, Minnesota, held Nov. 27-30, 2018.

<https://www.nationalwind.org/wp-content/uploads/2019/07/wwrm12proceedingsmarch2019-1.pdf>

*The auditory attributes of Golden Eagles: Do Golden (Aquila chrysaetos) and Bald Eagles (Haliaeetus leucocephalus) share the same auditory space?* Presented at the 176<sup>th</sup> Meeting of the Acoustical Society of America and 2018 Acoustics Week in Canada (Vol. 144, Issue 3, Pt. 2 of 2, p. 1792) in Victoria, British Columbia, Canada, held Nov. 5-9, 2018.

<https://acousticalsociety.org/176th-meeting-acoustical-society-of-america>

[https://acousticalsociety.org/wp-content/uploads/2018/10/PASA\\_144\\_3\\_pt2.pdf](https://acousticalsociety.org/wp-content/uploads/2018/10/PASA_144_3_pt2.pdf)

<https://asa.scitation.org/doi/10.1121/1.5067726>

*The highs and lows of eagle hearing: Mapping the auditory system of eagles.* Presented at the ExoticsCon 2018 meeting in Atlanta, Georgia, held Sept. 22-27, 2018.

<https://cloud.3dissue.com/131816/138446/219312/EC18-PG/index.html?r=32>:

<https://docplayer.net/120958762-Program-guinde-exoticscon-2018-exoticscon-org-building-exotics-excellence-one-city-one-conference.html>

*Calls of the bald eagle (Haliaeetus leucocephalus).* Presented at the 175<sup>th</sup> Meeting of the Acoustical Society of America (Vol. 143, Issue 3, Pt.2 of 2, p. 1897) in Minneapolis, Minnesota, held May 7-11,

2018.

<https://acousticasociety.org/program-of-175th-meeting-of-the-acoustical-society-of-america/>  
<https://asa.scitation.org/doi/10.1121/1.5036171>

*Eagles and wind turbines: Hearing assessment as a prelude to the development of acoustic deterrence tools.* Presented at the 41<sup>st</sup> meeting of the Association for Research in Otolaryngology (Vol: 41, p. 614-615) in San Diego, California, held Feb. 9-14, 2018.

[https://aro.org/wp-content/uploads-2020/02/2018/2018\\_ARO\\_Abstracts\\_ALL\\_PAGES.pdf](https://aro.org/wp-content/uploads-2020/02/2018/2018_ARO_Abstracts_ALL_PAGES.pdf)

## Networks/Collaborations Fostered

- Close collaboration established with colleagues at Sia, The Comanche Nation Ethno-Ornithological Initiative.
- Discussed potential collaboration with colleagues at Purdue University.
- Discussed potential collaboration with colleagues at DTBird.

## Websites/Social Media Featuring Project

UMN websites featuring information about this project:

- <https://vetmed.umn.edu/news/research-roundup-could-sound-keep-eagles-colliding-wind-turbines>
- <https://cla.umn.edu/slhs/news-events/story/eagle-ear-eye-how-raptors-hear>
- <https://twin-cities.umn.edu/news-events/research-brief-understanding-how-raptors-hear-may-help-prevent-future-wind-turbine>
- [https://raptor.umn.edu/sites/raptor.umn.edu/files/ratpor\\_release-fall\\_2017-3.pdf](https://raptor.umn.edu/sites/raptor.umn.edu/files/ratpor_release-fall_2017-3.pdf)
- [https://umn.edu/sites/raptor.umn.edu/files/raptor\\_release\\_spring\\_2018.pdf](https://umn.edu/sites/raptor.umn.edu/files/raptor_release_spring_2018.pdf)
- [https://raptor.umn.edu/sites/ratpro-umn.edu/files/trc\\_highlights\\_2019\\_update.pdf](https://raptor.umn.edu/sites/ratpro-umn.edu/files/trc_highlights_2019_update.pdf)

Photographs and updates on this project featured on the social media accounts of the University of Minnesota St. Anthony Falls Laboratory, The Raptor Center and the Speech Language and Hearing Department CATSS lab.

- SAFL Facebook Page: <https://www.facebook.com/saflumn/>
- SAFL Twitter Page: <https://twitter.com/saflumn>
- CATSS Lab Twitter Page: [https://twitter.com/UMN\\_CATSS](https://twitter.com/UMN_CATSS)
- The Raptor Center Facebook Page: <https://www.facebook.com/TheRaptorCenter>
  - <https://www.facebook.com/TheRaptorCenter/photos/how-well-can-eagles-hear-trc-is-currently-working-on-a-research-study-funded-by-/10156717182569656/>

## Press Releases Featuring Project

The Acoustical Society of America, through the auspices of the American Institute of Physics (AIP), featured a press release of our work that was embargoed for release until Wednesday, May 15, 2019 following the presentation entitled, *Behavioral responses suggest bald eagles closely monitor their immediate acoustic environment*, delivered at the Acoustical Society of America's spring meeting held in Louisville, Kentucky. The following are some of the news organizations that carried the report:

- AAAS EurekAlert! Science News: [https://www.eurekalert.org/pub\\_releases/2019-05/asoa-csp051019.php](https://www.eurekalert.org/pub_releases/2019-05/asoa-csp051019.php)
- Wind Energy News at Wind Daily: [https://www.winddaily.com/reports/Can\\_sound\\_protect\\_eagles\\_from\\_wind\\_turbine\\_collisions\\_99.html](https://www.winddaily.com/reports/Can_sound_protect_eagles_from_wind_turbine_collisions_99.html)
- Ornithology Exchange: <https://ornithologyexchange.org/forums/topic/40211-can-sound-protect-eagles-from-wind-turbine-collisions/>
- PhysOrg: <https://phys.org/news/2019-05-eagles-turbine-collisions.html>
- Vaaju: <https://vaaju.com/singapore/can-protect-eagles-from-wind-turbine-collisions/>
- The Wildlife Society: <https://wildlife.org/can-sound-keep-birds-and-bats-from-hitting-wind-turbines/>
- JustDial: <https://www.justdial.com/JdSocial/news/1557949693057000>
- HomelandSecurityReview: <https://homelandsecurityreview.com/2019/05/15/can-sound-protect-eagles-from-wind-turbine-collisions/>
- EnergyCentral: <https://energycentral.com/news/can-sound-protect-eagles-wind-turbine-collisions>
- Newswise: <https://www.newswise.com/articles/schedule-for-the-acoustical-society-of-america-press-conferences-with-live-webcasts-from-louisville>
- Birwatchingdaily: <https://www.birdwatchingdaily.com/news/conservation/searching-for-best-sound-to-help-eagles-avoid-wind-turbines/>
- The Latest: [https://thelatest.com/store/sound-protect-collisions-eagles-9859234?news\\_id=13718330](https://thelatest.com/store/sound-protect-collisions-eagles-9859234?news_id=13718330)
- Parallelstate: <https://parallelstate.com/news/can-sound-protect-eagles-from-wind-turbine-collisions/118816>
- Njus Media (Sweden): <https://www.njus.me/int/new/public-protection/0/6221682/can-sound-protect-eagles-from-wind-turbine-collisions>

In addition, the following sites have featured the project:

- Minnesota Daily: <https://www.mndaily.com/article/2019/12/n-umn-researchers-work-to-save-raptors-killed-by-wind-turbines>
- The Timberjay: <http://timberjay.com/stories/research-seeks-solutions,15794>
- StarTribune: <https://www.startribune.com/raptor-center-studies-what-birds-hear-in-step-toward-avoiding-wind-turbine-deaths/567358282/>
- Technology.org: <https://www.technology.org/2019/11/26/research-brief-understanding-how-raptors-hear-may-help-prevent-future-wind-turbine-deaths/>
- Miragenews: <https://www.miragenews.com/understanding-how-raptors-hear-may-help-prevent-future-wind-turbine-deaths/>
- Wind-Works: <http://www.wind-works.org/cms/index.php?id=90>
- Hearing-loss-causes-blogspot: <https://hearing-loss-causes.blogspot.com/2019/12/birds-hear-what-we-hear-new-research.html>
- Rivertowns: <https://www.rivertowns.net/news/science-and-nature/4813836-Birds-hear-what-we-hear-new-research-examines-raptor-hearing-range>
- Wind-Watch: <https://www.wind-watch.org/news/2019/12/04/umn-researchers-seek-to-save-raptors-killed-by-wind-turbines/>

- SOAR (Saving our Avian Resources): <https://soarraptors.org/2020/02/research-to-help-raptors/>
- Texasobserver: <https://www.texasobserver.org/bald-eagles-numbers-at-lake-buchanan-are-declining-no-ones-exactly-sure-why/>

## **Public Broadcasting Featuring Project**

- Oregon Public Broadcasting (OPB): <https://www.opb.org/news/article/sounds-eagles-wind-turbines-fatalities/>
- Northwest Public Broadcasting (NWPB): <https://www.nwpb.org/2019/06/01/to-drive-eagles-away-from-deadly-wind-turbines-researchers-turn-to-sound/>

## **Budget Status – Prime Recipient**

A detailed budget status is given in the worksheet *DE-EE0007881\_RPPR Tables\_QTR3\_8.1.18.xls* that was uploaded to the EERE PMC website with this report.

## **Certification of Compliance**

The information provided in this report is, to our best knowledge, accurate and complete as of the filing date of this report.

## **Appendix A. ABR Testing Procedure**

### **Animal Preparation and Monitoring During Procedures**

Animals were anesthetized with isoflurane to eliminate muscle activity and thereby maintain a stable, quiet recording environment. Anesthesia was initiated via mask induction using a mixture of humidified 4-5% isoflurane with 100% oxygen (O<sub>2</sub>) at a flow rate of 1-2 L/min. When deep sedation/general anesthesia was achieved, animals were intubated and maintained in a lightly sedated state with approximately 1.5 to 2.5% isoflurane mixed with 1-2 L/min O<sub>2</sub> throughout the recording session. Animals were fasted for 12-24 hours prior to anesthetization.

Respiratory rate and end-tidal CO<sub>2</sub> (EtCO<sub>2</sub>) were monitored throughout the recording session. Typically, respiratory rates were in the range of 10-20 breaths/min and EtCO<sub>2</sub> levels were in the range of 30-50 mm Hg. If respiratory rate was low and EtCO<sub>2</sub> was high, the recording session was paused to ventilate the bird. In addition, recordings were paused periodically to assess body (cloacal) temperature, and palpebral and/or corneal reflexes. When necessary, birds were cooled using chilled plastic bottles, or were heated using an electric blanket (Harvard Apparatus, Holliston, MA) to maintain body temperature between 39 and 40°C; recording sessions were paused and animals were cooled when body temperature reached 41°C. All recordings were conducted in an electrically-shielded, sound-attenuating chamber lined with acoustic foam and equipped with a webcam (either a commercially-available chamber or the custom-built MEARL-see Appendix B). A veterinarian continuously monitored subjects throughout recording sessions and during subsequent recovery from anesthesia. Following recording sessions, animals received supplemental fluids and electrolytes by subcutaneous administration of Ringer's lactated solution.

Protocols governing the care and use of animals participating in the study were approved by the University of Minnesota Institutional Animal Care and Use Committee, and required wildlife permits were acquired from the U.S. Fish and Wildlife Service and the Minnesota Department of Natural Resources.

### **Assessment of Auditory Function**

Auditory brainstem responses (ABRs) to a comprehensive battery of clicks and tone bursts varying in level and frequency were acquired and analyzed to assess auditory function. Using fine (30-gauge) platinum alloy subdermal needle electrodes positioned at the vertex (active, non-inverting), in the near vicinity of the outer ear aperture (reference, inverting) and over the musculature of the clavicle (ground), ABRs were recorded differentially (Grass Instruments, P511 AC preamplifier, West Warwick, RI). Voltages were amplified 100,000x, filtered (30 Hz-10 kHz) and digitized over a 15 ms epoch using a 20 kHz sampling rate. The transducer, a multi-field magnetic speaker (MF1, Tucker-Davis Technologies, Alachua, FL), was positioned 10 cm above one ear (typically the right ear). Symmetrically shaped tone bursts with 1 ms raised cosine on/off ramps and a 1 ms plateau were generated digitally (Tucker-Davis Technologies), alternated in polarity, and presented free-field at a rate of approximately 12.5 Hz; duration was increased to 9 ms with 3 ms on/off ramps when acquiring data for the 354 Hz stimulus. Click stimuli were 64  $\mu$ s in duration. Stimulus levels were calibrated and reported in decibels sound pressure level (dB SPL: referenced to 20  $\mu$ Pa). Trials with voltages exceeding 70  $\mu$ V were automatically rejected and the trial was repeated. A maximum of 500 trials was averaged for each waveform and two waveforms were obtained for each stimulus condition. The number of trials averaged per waveform was truncated

manually online when waveform reproducibility was achieved (i.e., waveform peaks and valleys replicated with subjective clarity) to facilitate data acquisition efficiency and to reduce anesthesia time.

Stimulus frequency was varied from 0.35 kHz to 8.0 kHz in one-half octave steps when studying bald eagles. The upper frequency was extended to 11.3 kHz when studying red-tailed hawks. Stimulus levels were decreased in 10 dB decrements from approximately 90 dB SPL to below threshold, and levels were adjusted in 5 dB steps near threshold. Responses to click stimuli were acquired in all eagles studied and in six red-tailed hawks.

## Data Analyses

Threshold was defined as the lowest stimulus level eliciting a replicable response. Low- and high-frequency flanks of threshold-frequency curves were fitted with least-squares linear regressions to compute the slope or rate of threshold change per octave. Peak latencies were measured from the onset of the stimulus, and therefore included air conduction time, estimated to be approximately 0.29 ms. Wave I amplitudes were computed using a triangulation procedure as described in Walsh *et al.* (1986); however, given the double-peaked nature of wave I, the base of the triangle was extended to the negativity following wave IB. Least squares linear regressions were used to fit log-transformed latency vs. level curves and log-transformed amplitude vs. level curves using the model,  $\ln(y) = \alpha + \beta x$ , where the y-intercept is represented by  $\alpha$  and slope is represented by  $\beta$ ; the model may be expressed alternatively as  $y = e(\beta x + \alpha)$ . In addition, a linear regression was fitted to the regression coefficient,  $-1/\beta$ , of latency-level curves and an exponential was fitted to  $\exp(\alpha)$  as a function of log-transformed frequency. Finally, polynomial functions were used to fit the regression coefficients,  $1/\beta$  and  $\exp(\alpha)$ , of amplitude-level curves as a function of log-transformed frequency.

Statistical analyses were performed using R (R Core Team, 2018 version 3.5.0). Results of all statistical tests were considered significant when  $P < .05$ .

A more detailed description of statistical tests performed and results for bald eagles and red-tailed hawks are provided in the McGee *et al.* (2019c) published manuscript and the associated electronic supplementary materials.

## **Appendix B. Design, Construction, and Verification of Mobile Evoked Auditory Response Lab (MEARL)**

### **Background**

The project titled *Detection and Perception of Sound by Eagles and Surrogate Raptors* seeks to assess, among other things, the hearing capabilities of bald eagles, golden eagles and red-tailed hawks. This assessment is performed using the Auditory Brainstem Response (ABR) method, which involves anesthetizing test subjects and positioning three, small subdermal sensors at specific locations on the bird's scalp during recording sessions. A series of acoustic stimuli (e.g. clicks, frequency specific tone bursts, as well as SAM and FM signals) were delivered to the bird via a speaker positioned along the midline at a constant distance in front of the bird. It was important that these tests were conducted in a controlled environment that limited the ambient acoustic noise so that the responses observed were only due to the selected stimuli. Ambient electrical noise needed to be attenuated as the electrodes were measuring potentials in the micro-volt range.

An ideal environment for these tests was located at the Center for Applied and Translational Sensory Science (CATSS) of University of Minnesota (UMN) Speech, Language and Hearing Department. The CATSS lab featured a large sound-attenuating, electrically shielded chamber for human testing. The majority of bald eagles and red-tailed hawks studied in this project were tested in this facility. However, the presence of golden eagles in Minnesota is relatively rare, so the yearly population of golden eagles at the University of Minnesota Raptor Center was not expected to be large enough for this study. As a result, the project team traveled to a partner facility with a large population of golden eagles. There was no suitable sound-attenuating, electrically shielded facility available at this location, so a mobile testing chamber was needed. The mobile testing chamber was transported to the golden eagle partner facility where testing was performed. This document provides details about the design and construction of the Mobile Evoked Auditory Response Laboratory (MEARL).

### **Design Criteria**

Design criteria for the MEARL were provided by researchers involved in the project. Veterinarians at the UMN Raptor center provided the minimum required interior dimensions and environmental conditions required for the raptors to be tested. Acousticians from the UMN Department of Speech, Language and Hearing Sciences provided input on the sound attenuation and electrical shielding requirements. Engineers at the UMN St. Anthony Falls Laboratory provided criteria that ensured transportability. Below is a table of the important criteria considered in the design of the MEARL.

#### **Veterinary Design Criteria**

- Interior Dimensions of at least 5ft long by 3ft wide by 2.5ft tall.
- Pass through access for anesthesia and health monitoring equipment.
- Interior LED lights and a camera to allow the test subject to be observed without opening the MEARL.
- Quick access to the interior of the MEARL in the event that the test subject needed veterinary attention.

#### **ABR Design Criteria**

- Acoustic attenuation of at least 25dB in the frequency range of approximately 100Hz to 20kHz

- Electrical shielding to limit the Electromagnetic Field (EMF) and reduce the electrical noise on the electrodes, increasing the signal-to-noise ratio of the ABR measurements.
- Pass through access for the electrodes and cables to the speaker emitting the stimuli.

### Transportability Criteria

- Must be able to be disassembled enough to fit through a 30” wide doorway.
- Must be capable of being transported in the bed of a pick-up truck or trailer.
- Ideally it can be disassembled and light weight enough to be carried by one or two people.

### Cost Criteria

- Total budget for materials allocated for the MEARL under the DOE grant was \$8,000.

## Materials List

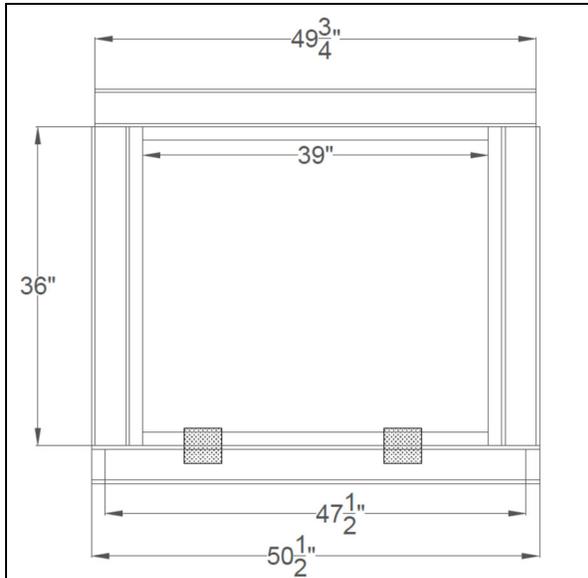
A list of materials purchased for the construction of the MEARL is provided in Table 6.

**Table 6. Materials List for Construction of MEARL**

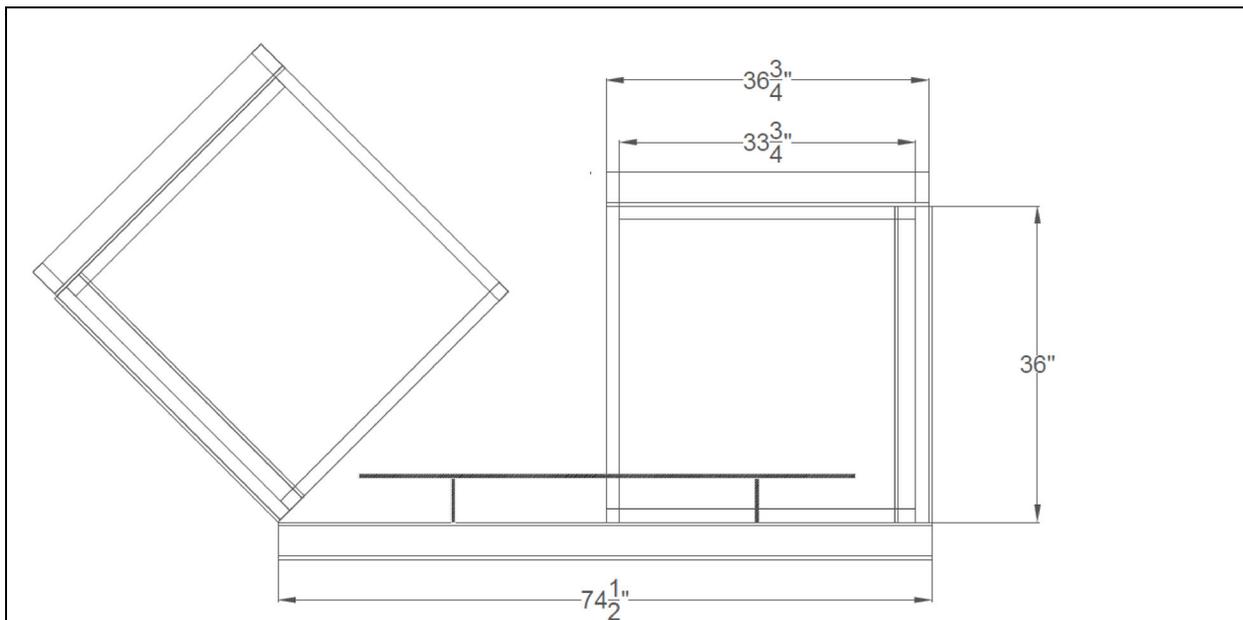
| <i>Item</i>   | <i>Vendor</i>        | <i>Quantity</i> | <i>Purpose</i>                              |
|---|----------------------|-----------------|---|
| Alpha Linear Foam 2'x4'x3"                            | Acoustical Solutions | 3               | Acoustical Attenuation                      |
| Titebond GreenChoice Adhesive                         | Acoustical Solutions | 5               | Adhesive for Acoustical Foam                |
| 10' USB 3.0 Extension Cable                           | Amazon               | 1               | Extend the webcam cable                     |
| LED Undercabinet Lighting                             | Amazon               | 1               | Illuminate the interior of MEARL            |
| Logitech C922x Pro Stream Webcam                      | Amazon               | 1               | Provide video feed of the interior of MEARL |
| Roxul Safe 'n Sound Insulation                        | Home Depot           | 2               | Acoustical Attenuation                      |
| 11/32" Sanded Plywood                                 | Home Depot           | 10              | Walls of the MEARL                          |
| 2x4" - 96" Studs                                      | Home Depot           | 26              | Structure of the MEARL                      |
| 4" Square Door Hinge                                  | Home Depot           | 4               | Doors of the MEARL                          |
| 1-1/4" Construction screws                            | Home Depot           | 3 boxes         | General construction fastener               |
| 3" Construction Screws                                | Home Depot           | 2 boxes         | General construction fastener               |
| 15A 125V Angle plug                                   | Home Depot           | 1               | Grounding cable plug                        |
| 5/16"-18x6" Hex Bolts                                 | Home Depot           | 1 box           | Fastening the walls of the MEARL together   |
| 5/16"-18x3/8" Tee Nut                                 | Home Depot           | 16              | Fastening the walls of the MEARL together   |
| Loctite 5Min Epoxy                                    | Home Depot           | 1               | Securing the tee-nuts                       |
| PL300 Foamboard adhesive                              | Home Depot           | 12              | Adhesive for Acoustical Foam                |
| #12x1-1/4" Wood Screws                                | Home Depot           | 6 boxes         | Attaching handles and hinges                |
| Door Pulls (Handles)                                  | Home Depot           | 20              | Handles to transport MEARL                  |
| 48"x1"x1/8" Flat Aluminum Bar                         | Home Depot           | 1               | Mounting bracket for the LED lights         |
| 1/4"-20x 12" Thread Rod                               | Home Depot           | 4               | Mounting bracket for the LED lights         |
| Highly Conductive Copper Tape 2" wide x 18 yards long | McMaster-Carr        | 1               | Electrical Shielding                        |
| 10 AWG ultra-flexible wire                            | McMaster-Carr        | 25ft            | Electrical Shielding Ground                 |
| Steel Draw Latch                                      | McMaster-Carr        | 6               | MEARL Closure                               |
| Plastic Load-rated pull handle                        | McMaster-Carr        | 8               | Handles to transport MEARL                  |
| Neoprene Foam Strip with Adhesive back 5/16" thick    | McMaster-Carr        | 50ft            | MEARL Closure sealing                       |
| Hollow Foam Rubber Seal - 3/16"                       | McMaster-Carr        | 20ft            | MEARL Closure sealing                       |
| 24"x48"x1/2" HDPE sheet                               | McMaster-Carr        | 1               | Bed for test subject                        |
| Aluminum Male-Female threaded standoff 1/4"-20 x 4"   | McMaster-Carr        | 4               | Support for test subject bed                |
| 16 Count Copper Mesh 48" x 48"                        | ThorLabs             | 11              | Electrical shielding                        |

## Construction

Prior to construction of the MEARL, full design drawings were produced in AutoCAD. These drawings aided in the determination of raw material quantities (lumber, insulation, copper mesh, etc.). Figure 35 and Figure 36 show a sample of these construction drawings.



**Figure 35. A construction drawing of the MEARL. This view is a profile view of the end of the MEARL showing the dimensions of enclosure and the location of the hinges.**



**Figure 36. A construction drawing of the MEARL showing a profile view of the side. Dimensions important for the construction of the frame are called out in the drawing.**

Construction of the MEARL began on September 7, 2017 at the St. Anthony Falls Laboratory with the frame of the base. The basic construction of the MEARL was 2x4 frames sheathed on each side in 1 1/32" plywood with Roxul Safe 'n Sound insulation and copper wire mesh between the layers of plywood. Nine different panels were constructed using this method. Each panel by itself was light weight enough and compact enough to be easily transported. Using 16 bolts and 4 hinges, the panels could be assembled into a fully enclosed box. The copper wire mesh wrapped around the edges of each panel so that it made contact with the copper mesh of the adjacent panels, completing the electrical shielding around the MEARL (Figure 37 and Figure 38).



**Figure 37. A photograph of the base of the MEARL showing the 2x4 lumber frame with the copper wire mesh stretched over it.**

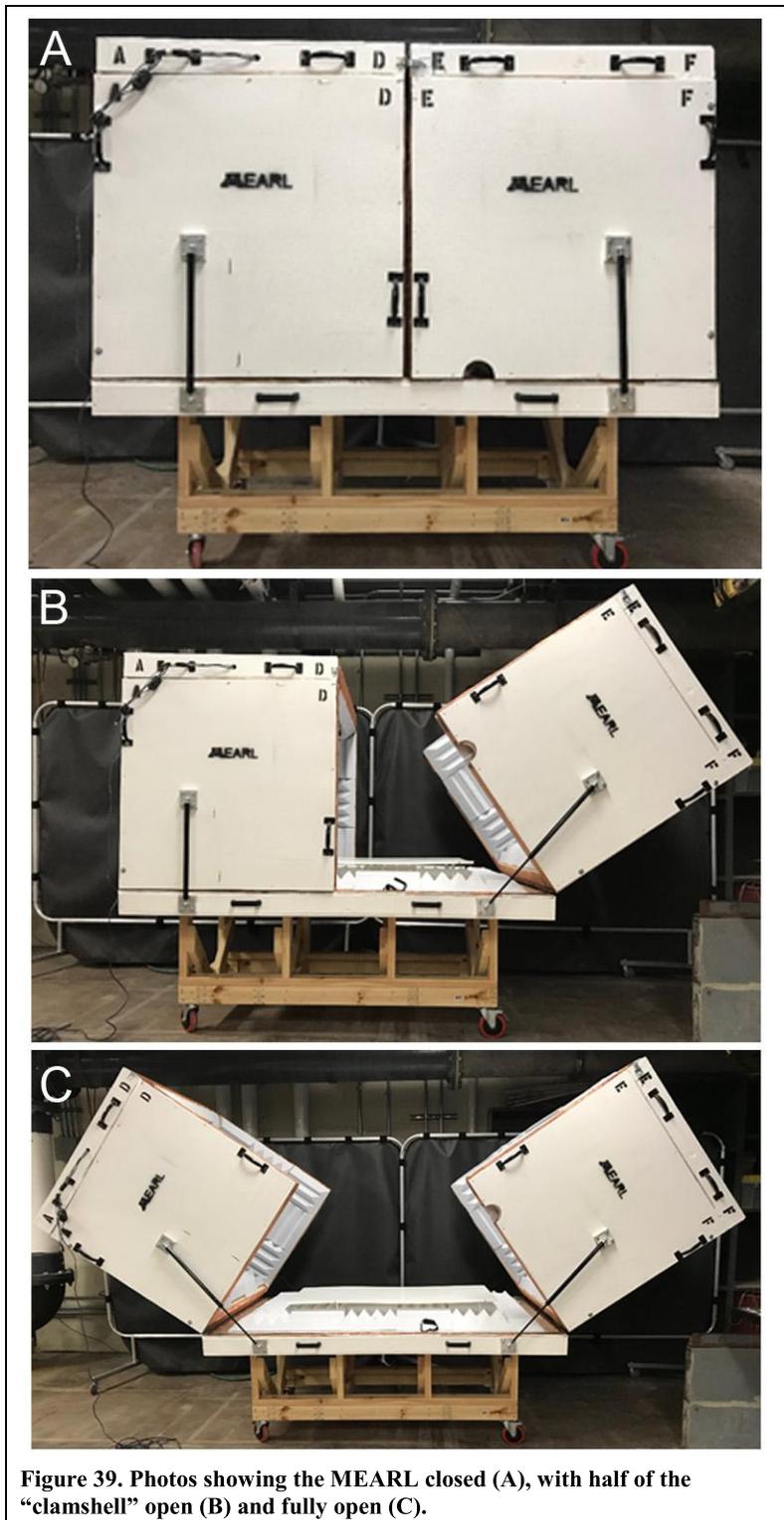


**Figure 38. One of the side panels of the MEARL before the final layer of plywood was installed. The Roxul Safe 'n Sound insulation is visible. On the top and left edge of the panel the wire mesh is wrapped around to make contact with the next panel.**

The top portion of the MEARL was constructed in two halves that hinge at the base to open in a “clamshell” fashion as shown in the figures below. This method of opening the MEARL provides nearly unrestricted access to the test subject when opened. Cables and anesthesia lines can be routed through a small cut out at the bottom of the “clamshell.” Gas springs assist in opening the halves of MEARL and prevent the clamshell from hinging too far open. Figure 39 shows the MEARL with the “clamshell” top closed, half open and fully open.

The entire interior of the MEARL is covered with 3” thick acoustical foam

that is adhered to the plywood (Figure 40). The linear pattern of this foam was arranged in a 1ft x 1ft square checkerboard fashion.



**Figure 39. Photos showing the MEARL closed (A), with half of the “clamshell” open (B) and fully open (C).**

The platform for the test subject is comprised of a 2' x 4' high-density polyethylene plastic sheet supported by 4 aluminum stand-offs that are attached to the base of the MEARL and extend up through the 3" of acoustical foam (Figure 40).

The webcam and LED light strips are mounted to one of the top panels of the MEARL with steel threaded rods (Figure 40). The USB cable for the webcam and the power cable for the lights are routed to the exterior of the MEARL.

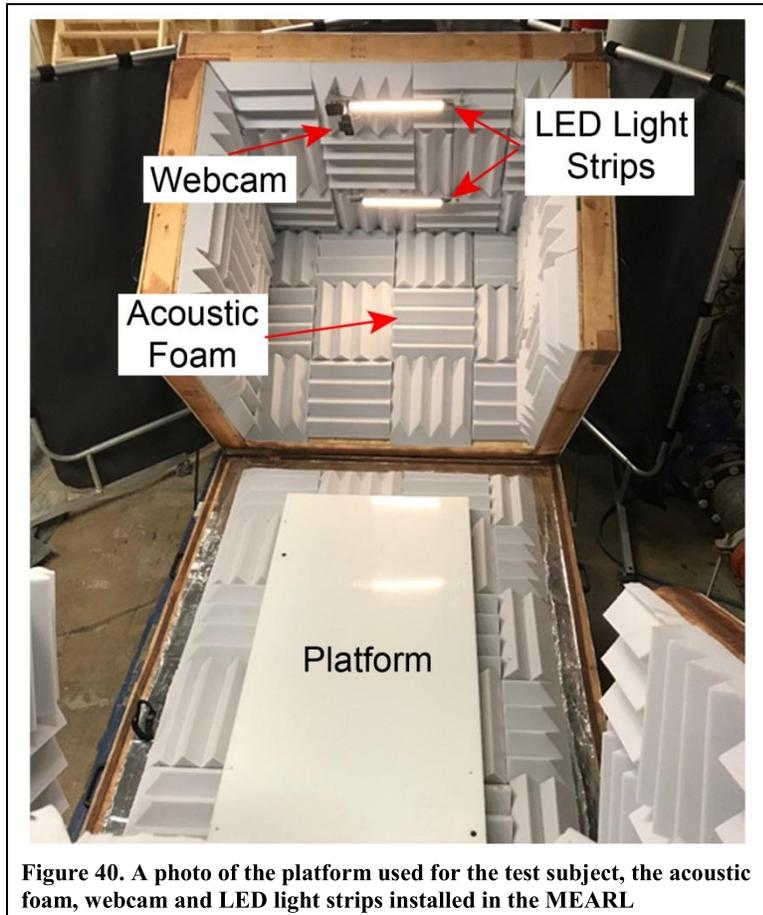


Figure 40. A photo of the platform used for the test subject, the acoustic foam, webcam and LED light strips installed in the MEARL

The pass-through access port for anesthesia and health monitoring equipment, as well as for recording electrodes and heating blanket and speaker cables is shown in Figure 41.



**Figure 41.** Photo of the side of the MEARL with the cable pass through port highlighted.

A photograph of MEARL fully opened and with an anesthetized golden eagle being prepared for ABR studies is shown in Figure 42.



**Figure 42.** A golden eagle is prepared for ABR testing in the MEARL.

A photograph of an anesthetized golden eagle fully prepared for ABR studies is shown in Figure 43.

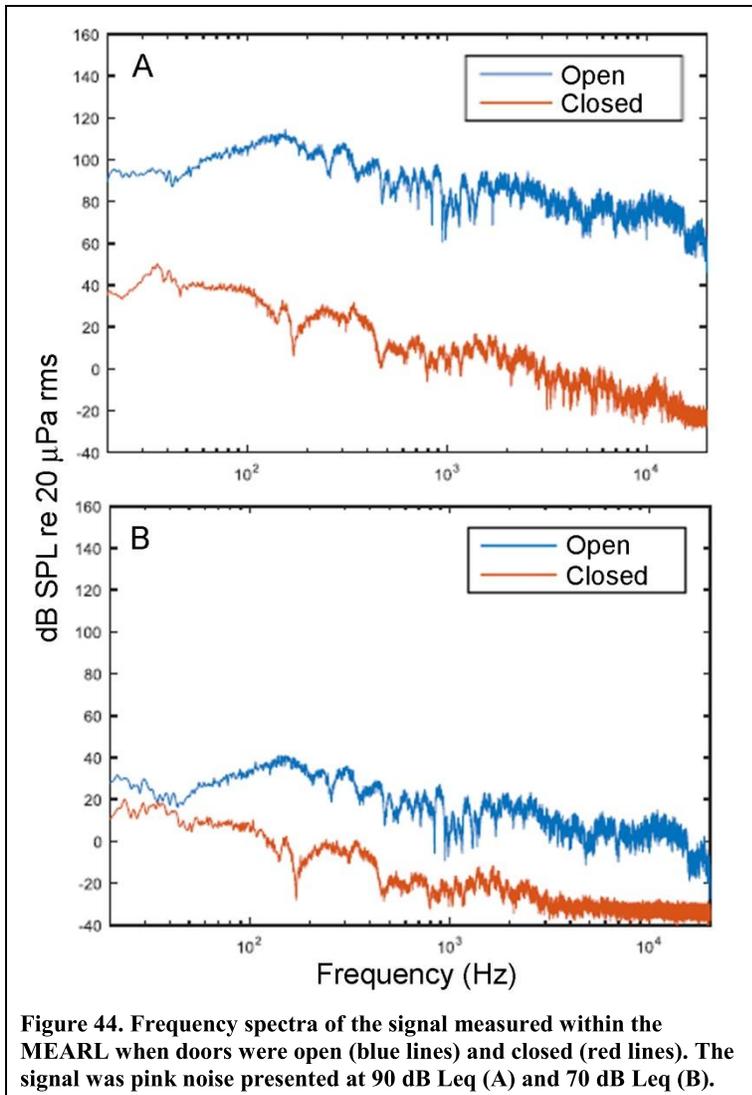


Figure 43. An anesthetized golden eagle in the MEARL fully prepared for ABR studies and prior to closing the doors of the MEARL.

## Performance Testing

Before being used for ABR testing on raptors, the acoustic attenuation properties of the MEARL were tested in the CATSS lab at the University of Minnesota. The testing chamber at the CATSS lab features a large array of speakers and is large enough to fit the MEARL inside it. To get a baseline of noise inside the CATSS lab chamber, only the base section of the MEARL was placed inside the chamber. A microphone was then positioned on the platform where a test subject would be placed, and a pink noise signal was emitted from the speakers at 90 dB and 70 dB  $L_{eq}$ . The top of the MEARL was then placed on top of the base and the same test was repeated.

Figure 44A shows that for the 90 dB  $L_{eq}$  test, the MEARL attenuated the pink noise signal by approximately 50 dB. Figure 44B shows that the MEARL attenuated the 70 dB signal by approximately 30 dB at all frequencies higher than 100 Hz. This test showed that the MEARL sufficiently attenuated acoustic noise to allow for accurate ABR studies.



**Figure 44.** Frequency spectra of the signal measured within the MEARL when doors were open (blue lines) and closed (red lines). The signal was pink noise presented at 90 dB Leq (A) and 70 dB Leq (B).

## Appendix C. Procedure used to Generate the Evoked Potential to Behavioral Threshold-Frequency Correction Curve

A threshold-frequency correction curve was generated to equate evoked potential thresholds acquired in this study to absolute thresholds acquired behaviorally by other investigators. Because the temporal integration of information contained in longer tonal stimuli permits a more accurate estimate of absolute sensitivity (Dooling *et al.* 1978; Dooling 1979; Barton *et al.* 1984; Dooling and Searcy 1985; Klump and Maier 1990; Okanoya and Dooling 1990; Saunders and Salvi 1993; Pohl *et al.* 2013), relatively long stimulus durations (e.g., typically in the range of 400 ms to several seconds) were employed in most of the behavioral studies referenced in this investigation. In contrast, evoked potentials are “onset” responses triggered by stimuli with relatively fast rise times (typically in the range of 1 ms or less) permitting the synchronous discharge of the all-or-none action potentials of auditory neurons (Goldstein and Kiang 1958; Picton *et al.* 1977; Burkard 1991); stimulus duration therefore is not a significant variable when acquiring ABR or VIIIth nerve compound action potential (CAP) responses (Hecox *et al.* 1976).

The threshold-correction curve was constructed by first fitting 3rd order polynomials to digitized threshold-frequency curves taken from avian species for which both behavioral and evoked potential thresholds were available in the literature (Table 7). When considering evoked potential studies, ABR and/or CAP thresholds were included in the analysis. Data from a total of 9 species were utilized to generate the correction curve, although data from 2 species were combined consistent with the reporting method used by one of the investigators (Gall *et al.* 2011). Second, fitted curves (n=41 threshold-frequency curves) were then sampled in half-octave steps throughout the responsive frequency range, and averages were calculated separately for behavioral data and evoked potential data for each species included in the analysis when multiple studies for a given species were identified. Third, threshold-frequency curves derived from behavioral studies were subtracted from threshold-frequency curves derived from evoked potential studies for each species, and differences were averaged across species, resulting in the threshold-frequency correction curve used in the investigation. These values were then subtracted from observed bald eagle and red-tailed hawk ABR threshold values to approximate absolute thresholds. The threshold corrections indicate, at least in part, the extent to which longer duration stimuli permit greater signal integration time and concomitant improvement of estimated thresholds, more accurately estimating absolute threshold values across stimulus frequency. The frequency dependence of threshold correction factors is consistent with that reported for individual avian species by others (Brittan-Powell *et al.* 2002, 2010; Köppl and Gleich 2007; Henry and Lucas 2008; Crowell *et al.* 2016; Maxwell *et al.* 2016).

**Table 7. Species, General Method, and Source of Threshold-Frequency Curves Used to Compute the Avian Threshold-Frequency Correction Curve**

| Order        | Common Name  | Scientific Name           | Method                | Anesthetic | Reference                   |
|--------------|--------------|---------------------------|-----------------------|------------|-----------------------------|
| Anseriformes | Lesser Scaup | <i>Aythya affinis</i>     | Behavior              |            | Crowell et al. (2016)       |
|              |              |                           | ABR                   | Isoflurane | Crowell et al. (2016)       |
|              | Mallard      | <i>Anas platyrhynchos</i> | Behavior              |            | Trainer (1946) <sup>a</sup> |
|              |              |                           | Behavior <sup>b</sup> |            | Hill (2017)                 |

| Order         | Common Name                       | Scientific Name           | Method                | Anesthetic                                 | Reference                              |
|---------------|-----------------------------------|---------------------------|-----------------------|--|--|
| Anseriformes  | Mallard                           | <i>Anas platyrhynchos</i> | ABR <sup>c</sup>      | Awake                                      | Dmitrieva and Gottlieb (1992)          |
| Columbiformes | Rock Dove (Pigeon)                | <i>Columba livia</i>      | Behavior <sup>d</sup> |  | Trainer (1946) <sup>a</sup>            |
|               |                                   |                           | Behavior              |  | Heise (1953)                           |
|               |                                   |                           | Behavior              |  | Stebbins (1970)                        |
|               |                                   |                           | Behavior              |  | Harrison and Furumoto (1971)           |
|               |                                   |                           | Behavior              |  | Hienz et al. (1977)                    |
|               |                                   |                           | Behavior <sup>d</sup> |  | Goerdel-Leich and Schwartzkopff (1984) |
|               |                                   |                           | Behavior <sup>b</sup> |  | Heffner et al. (2013)                  |
|               |                                   |                           | CAP                   | Pentobarbital                              | Gummer et al. (1987)                   |
|               |                                   |                           | CAP                   | Ket/xylazine                               | Reng et al. (2001)                     |
| Galliformes   | Chicken                           | <i>Gallus gallus</i>      | Behavior              |  | Gray and Rubel (1985)                  |
|               |                                   |                           | Behavior              |  | Saunders and Salvi (1993)              |
|               |                                   |                           | Behavior <sup>b</sup> |  | Hill et al. (2014)                     |
|               |                                   |                           | CAP                   | Ket/chloropent                             | Rebillard and Rubel (1981)             |
|               |                                   |                           | ABR                   | Ket/equithesin                             | Tucci and Rubel (1990)                 |
|               |                                   |                           | CAP                   | Ket/pentobarbital                          | Patuzzi and Bull (1991)                |
|               |                                   |                           | CAP                   | Ket/xylazine initially, then pentobarbital | Salvi et al. (1992)                    |
|               |                                   |                           | CAP                   | Ket/pentobarbital                          | Chen et al. (1993)                     |
| Passeriformes | Atlantic Canary <sup>e</sup>      | <i>Serinus canaria</i>    | Behavior              |  | Okanoya and Dooling (1985)             |
|               |                                   |                           | Behavior              |  | Okanoya and Dooling (1987)             |
|               |                                   |                           | ABR                   | Ket/diazepam                               | Brittan-Powell et al. (2010)           |
|               |                                   |                           | ABR <sup>f</sup>      | Ket/diazepam                               | Noirot et al. (2011)                   |
|               | Brown-headed Cowbird <sup>g</sup> | <i>Molothrus ater</i>     | Behavior              |  | Hienz et al. (1977)                    |

| Order          | Common Name                       | Scientific Name                     | Method          | Anesthetic               | Reference   |
|----------------|-----------------------------------|-------------------------------------|-----------------|--------------------------|---|
| Passeriformes  | Red-winged Blackbird <sup>g</sup> | <i>Agelaius phoeniceus</i>          | Behavior        |                          | Hienz et al. (1977)                                   |
|                |                                   |                                     | ABR             | Ket/midazolam            | Gall et al. (2011)                                    |
| Psittaciformes | Budgerigar                        | <i>Melopsittacus undulatus</i>      | Behavior        |                          | Saunders and Dooling (1974)                           |
|                |                                   |                                     | Behavior        |                          | Dooling and Saunders (1975)                           |
|                |                                   |                                     | Behavior        |                          | Saunders et al. (1979)                                |
|                |                                   |                                     | Behavior        |                          | Saunders and Pallone (1980)                           |
|                |                                   |                                     | Behavior        |                          | Okanoya and Dooling (1987)                            |
|                |                                   |                                     | Behavior        |                          | Hashino et al. (1988)                                 |
|                |                                   |                                     | Behavior        |                          | Hashino and Sokabe (1989)                             |
|                |                                   |                                     | Behavior<br>ABR | Ket/diazepam             | Heffner et al. (2016)<br>Brittan-Powell et al. (2002) |
| Suliformes     | Great Cormorant                   | <i>Phalacrocorax carbo sinensis</i> | Behavior        |                          | Maxwell et al. (2016)                                 |
|                |                                   |                                     | ABR             | ? "lightly anesthetized" | Maxwell et al. (2016)                                 |

Abbreviations: ABR-auditory brainstem response; CAP-compound action potential of the eighth nerve; ket-ketamine

<sup>a</sup>Source of Trainer (1946) data was Fay (1988)

<sup>b</sup>Threshold values included in curve fitting were limited to frequencies  $\geq 125$  Hz to emphasize frequency region of interest

<sup>c</sup>ABRs were recorded intracranially from 2-day old birds

<sup>d</sup>Median threshold values were reported

<sup>e</sup>Includes German Roller and American Singer strains; Belgian Waterslayers were excluded due to a sex-linked genetic mutation leading to hearing impairment (Wright et al., 2004)

<sup>f</sup>Threshold values for brown-headed cowbirds and red-winged blackbirds reported by Gall et al. (2011) were combined and averaged but separated by sex. Therefore, we averaged values from Gall et al. (2011) across sex to permit comparison with behavioral thresholds reported by Hienz et al. (1977) for each species. We then averaged threshold values reported by Hienz et al. (1977) for the purpose of comparison.

<sup>g</sup>Given the limited frequency range of data in Noiroot et al. (2011), we combined it with the data from Brittan-Powell et al. (2010) prior to fitting the frequency-threshold curve

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## Appendix D. Procedure used to Compare Threshold-Frequency Data with other Avian Species

Average bald eagle, golden eagle and red-tailed hawk threshold-frequency curves resulting from this study were compared to average threshold-frequency curves of species belonging to five taxonomic orders (Figure 15): Accipitriformes (n=2 species), Falconiformes (n=1), Strigiformes (n=13), Passeriformes (Oscines, n=20) and Psittaciformes (n=5). Generally, threshold-frequency curves were extracted from data acquired from behavioral studies or physiological (heart-rate) conditioning studies reported in the literature (Table 8). However, when behavioral data were unavailable, threshold-frequency curves were derived from single unit or multiunit recordings of neurons within auditory nuclei (i.e., cochlear nuclei, CN or the dorsolateral mesencephalic nucleus, nMLD). In those cases, the most sensitive estimates of thresholds at characteristic frequency were extracted using a 0.25 octave-wide averaging window. Threshold-frequency data from 41 species (n=58 data sets) were digitized and each curve was fitted by a 3<sup>rd</sup>-order polynomial. Fitted curves were then sampled in half-octave steps throughout the responsive frequency range and averaged (if more than a single data set was available) to generate average threshold-frequency curves representing each species included in the analysis. Subsequently, these curves were averaged across species to obtain the mean±1 s.d. for each taxonomic order specified above. However, given the low sample size and similarity of results for species representing Accipitriformes and Falconiformes, threshold-frequency data from these orders were combined into a single threshold-frequency data set (average±1 s.d.) for diurnal raptors.

Table 8. Species, Sex, Age, Procedure, and Source of Other Avian Threshold-Frequency Curves

| Order                  | Common Name                  | Scientific Name              | Number F/M/U <sup>a</sup> | Age <sup>b</sup> | Procedure   | Reference                   |
|------------------------|------------------------------|------------------------------|---------------------------|------------------|---|-----------------------------|
| <b>Accipitriformes</b> |                              |                              |                           |                  |   |                             |
|                        | Brown Goshawk                | <i>Accipiter fasciatus</i>   | 0/0/1                     |                  | nMLD single unit and multiunit thresholds <sup>c</sup>                      | Calford (1988)              |
|                        | Eurasian Sparrowhawk         | <i>Accipiter nisus</i>       | 1/1/0                     | 4-11 m           | Operant conditioning for food reward  | Klump et al. (1986)         |
| <b>Falconiformes</b>   |                              |                              |                           |                  |   |                             |
|                        | American Kestrel             | <i>Falco sparverius</i>      | 0/0/1                     |                  | Instrumental shock avoidance  | Trainer (1946) <sup>d</sup> |
| <b>Passeriformes</b>   |                              |                              |                           |                  |   |                             |
|                        | American Crow                | <i>Corvus brachyrhynchos</i> | 0/0/1                     |                  | Instrumental shock avoidance  | Trainer (1946) <sup>d</sup> |
|                        | American Robin               | <i>Turdus migratorius</i>    | 0/0/1 <sup>e</sup>        | 74 g             | CN single unit thresholds <sup>f</sup>                                      | Konishi (1970)              |
|                        | Atlantic Canary <sup>g</sup> | <i>Serinus canaria</i>       | 2/2/0                     | adult            | Operant conditioning for food reward/ environment darkened for false alarms | Okanoya and Dooling (1985)  |

| <b>Order</b>                 |                            |                                 |                          |   |                             |
|------------------------------|----------------------------|---------------------------------|--------------------------|---|-----------------------------|
| <b>Common Name</b>           | <b>Scientific Name</b>     | <b>Number F/M/U<sup>a</sup></b> | <b>Age<sup>b</sup></b>   | <b>Procedure</b>  | <b>Reference</b>            |
| Atlantic Canary <sup>g</sup> | <i>Serinus canaria</i>     | 0/1/0                           |                          | Operant conditioning for food reward  | Okanoya and Dooling (1987)  |
| Blue Jay                     | <i>Cyanocitta cristata</i> | 0/0/2                           | 1 y                      | Operant conditioning for food reward  | Cohen et al. (1978)         |
| Brown-headed Cowbird         | <i>Molothrus ater</i>      | 3/3/0                           |                          | Operant conditioning for food reward/ environment darkened for false alarms         | Hienz et al. (1977)         |
| Chipping Sparrow             | <i>Spizella passerina</i>  | 0/0/1                           | 10 g                     | CN single unit thresholds <sup>f</sup>  | Konishi (1970)              |
| Common Starling              | <i>Sturnus vulgaris</i>    | 0/0/6 <sup>h,i</sup>            |                          | Instrumental shock avoidance  | Trainer (1946) <sup>d</sup> |
|                              |                            | 0/0/7 <sup>h</sup>              |                          | Heart rate conditioning with shock avoidance  | Kuhn et al. (1982)          |
|                              |                            | 0/1/0                           |                          | Operant conditioning for food reward  | Dooling et al. (1986)       |
|                              |                            | 0/0/4                           | 65-75 g                  | Operant conditioning for food reward/ environment darkened for false alarms         | Marean et al. (1993)        |
|                              |                            | 3/3/0                           | 6-12 m                   | Operant conditioning for food reward/ environment darkened for false alarms         | Langemann et al. (1999)     |
| Dark-eyed Junco              | <i>Junca hyemalis</i>      | 0/0/1 <sup>e</sup>              | 20 g                     | CN single unit thresholds <sup>f</sup>  | Konishi (1970)              |
| Eurasian Bullfinch           | <i>Pyrrhula pyrrhula</i>   | 0/0/4                           |                          | Operant conditioning for food reward  | Schwartzkopff (1948)        |
| Field Sparrow                | <i>Spizella pusilla</i>    | 0/2/0                           |                          | Instrumental shock avoidance  | Dooling et al. (1979)       |
| Great Tit                    | <i>Parus major</i>         | 4/3/0 <sup>h,i</sup>            | within 1 <sup>st</sup> y | Operant conditioning for food reward  | Langemann et al. (1998)     |
| Hooded Crow                  | <i>Corvus cornix</i>       | 0/0/2-4 <sup>h</sup>            |                          | Operant conditioning for food reward/ environment darkened for false alarms/ misses | Jensen and Klokke (2006)    |

| <b>Order</b>          |   |                                 |                        |   |                             |  |
|-----------------------|---|---------------------------------|------------------------|---|-----------------------------|--|
| <b>Common Name</b>    | <b>Scientific Name</b>                  | <b>Number F/M/U<sup>a</sup></b> | <b>Age<sup>b</sup></b> | <b>Procedure</b>  | <b>Reference</b>            |  |
| House Finch           | <i>Haemorhous mexicanus<sup>j</sup></i> | 2/2/0                           | 1-5 y                  | Instrumental shock avoidance  | Dooling et al. (1978)       |  |
| House Sparrow         | <i>Passer domesticus</i>                | 0/0/1 <sup>e</sup>              | 25 g                   | CN single unit thresholds <sup>f</sup>                                      | Konishi (1970)              |  |
| Red-billed Firefinch  | <i>Lagonosticta senegala</i>            | 2/2/0                           | 2-5 y                  | Operant conditioning for food reward/ environment darkened for false alarms | Lohr et al. (2004)          |  |
| Red-winged Blackbird  | <i>Agelaius phoeniceus</i>              | 3/7/0                           |                        | Operant conditioning for food reward/ environment darkened for false alarms | Hienz et al. (1977)         |  |
| Song Sparrow          | <i>Melospiza melodia</i>                | 0/1/0                           |                        | Operant conditioning for food reward  | Okanoya and Dooling (1987)  |  |
|                       |   | 1/2/0                           | 1-6 y                  | Operant conditioning for food reward/ environment darkened for false alarms | Okanoya and Dooling (1988)  |  |
| Swamp Sparrow         | <i>Melospiza georgiana</i>              | 0/1/0                           |                        | Operant conditioning for food reward  | Okanoya and Dooling (1987)  |  |
|                       |   | 0/2/0                           | 1-6 y                  | Operant conditioning for food reward/ environment darkened for false alarms | Okanoya and Dooling (1988)  |  |
| Western Meadowlark    | <i>Sturnella neglecta</i>               | 0/0/1 <sup>e</sup>              | 100 g                  | CN single unit thresholds <sup>f</sup>                                      | Konishi (1970)              |  |
| Zebra Finch           | <i>Taeniopygia guttata</i>              | 0/1/0                           |                        | Operant conditioning for food reward  | Okanoya and Dooling (1987)  |  |
|                       |   | 3/2/0                           |                        | Operant conditioning for food reward/ environment darkened for false alarms | Hashino and Okanoya (1989)  |  |
| <b>Psittaciformes</b> |   |                                 |                        |   |                             |  |
| Bourke's Parrot       | <i>Neopsephotus bourkii<sup>k</sup></i> |                                 |                        |   | Dooling (2002) <sup>l</sup> |  |
| Budgerigar            | <i>Melopsittacus undulatus</i>          | 0/0/4                           | 16 w                   | Instrumental shock avoidance  | Saunders and Dooling (1974) |  |

| <b>Order</b>            |                                |                                 |                                 |                                      |                                   |
|-------------------------|--------------------------------|---------------------------------|---------------------------------|--------------------------------------|-----------------------------------|
| <b>Common Name</b>      | <b>Scientific Name</b>         | <b>Number F/M/U<sup>a</sup></b> | <b>Age<sup>b</sup></b>          | <b>Procedure</b>                     | <b>Reference</b>                  |
| Budgerigar              | <i>Melopsittacus undulatus</i> | 2/2/0                           | 6-16 w                          | Instrumental shock avoidance         | Dooling and Saunders (1975)       |
|                         |                                | 0/0/6                           | 24-40 w                         | Instrumental shock avoidance         | Saunders et al. (1979)            |
|                         |                                | 0/0/4                           | 6-12 m                          | Instrumental shock avoidance         | Saunders and Pallone (1980)       |
|                         |                                | 0/2/0                           |                                 | Operant conditioning for food reward | Okanoya and Dooling (1987)        |
|                         |                                | 0/2/0                           | ~ 1 y                           | Instrumental shock avoidance         | Hashino et al. (1988)             |
|                         |                                | 0/7/0                           |                                 | Instrumental shock avoidance         | Hashino and Sokabe (1989)         |
|                         |                                | 2/1/0                           | ~6 m                            | Instrumental shock avoidance         | Heffner et al. (2016)             |
| Cockatiel               | <i>Nymphicus hollandicus</i>   | 0/1/0                           |                                 | Operant conditioning for food reward | Okanoya and Dooling (1987)        |
| Kea                     | <i>Nestor notabilis</i>        | 0/3/0                           | 1 juvenile, 1 subadult, 1 adult | Operant conditioning for food reward | Schwing et al. (2016)             |
| Orange-fronted Parakeet | <i>Eupsittula canicularis</i>  | 0/0/5                           | 5-20 m                          | Operant conditioning for food reward | Wright et al. (2003)              |
| <b>Strigiformes</b>     |                                |                                 |                                 |                                      |                                   |
| African Wood Owl        | <i>Strix woodfordii</i>        | 0/0/2                           | 1 y, 2 y                        | Operant conditioning                 | Nieboer and Van der Paardt (1977) |
| Barn Owl                | <i>Tyto alba<sup>m</sup></i>   | 0/0/1 <sup>e</sup>              |                                 | Operant conditioning for food reward | Konishi (1973)                    |
|                         | <i>Tyto alba guttata</i>       | 0/0/3 <sup>i</sup>              | 12-24 m                         | Operant conditioning for food reward | Dyson et al. (1998)               |
|                         | <i>Tyto alba</i>               | 0/0/4                           | 14-25 m                         | Operant conditioning for food reward | Krumm et al. (2017)               |
| Brown Fish Owl          | <i>Ketupa zeylonensis</i>      | 0/0/1                           | Adult                           | Operant conditioning                 | Van Dijk (1973)                   |
| Eurasian Eagle-Owl      | <i>Bubo bubo</i>               | 0/0/1                           | 1.5 y                           | Operant conditioning                 | Van Dijk (1973)                   |
| Eurasian Scops Owl      | <i>Otus scops</i>              | 0/0/1                           | 3.5 y                           | Operant conditioning                 | Van Dijk (1973)                   |
| Great Horned Owl        | <i>Bubo virginianus</i>        | 0/0/1                           |                                 | Instrumental shock avoidance         | Trainer (1946) <sup>d</sup>       |

| Order                              |                        |                           |                  |                      |                 |
|------------------------------------|------------------------|---------------------------|------------------|----------------------|-----------------|
| Common Name                        | Scientific Name        | Number F/M/U <sup>a</sup> | Age <sup>b</sup> | Procedure            | Reference       |
| Long-eared Owl                     | <i>Asio otus</i>       | 0/0/6                     | 0.5-≥1 y         | Operant conditioning | Van Dijk (1973) |
| Mottled Owl                        | <i>Strix virgata</i>   | 0/0/1                     | >5.5 y           | Operant conditioning | Van Dijk (1973) |
| Snowy Owl <sup>o</sup>             | <i>Bubo scandiacus</i> | 0/0/2                     | >6.5 y           | Operant conditioning | Van Dijk (1973) |
| Spot-bellied Eagle-Owl             | <i>Bubo nipalensis</i> | 0/0/1                     | 1.5 y            | Operant conditioning | Van Dijk (1973) |
| Spotted Wood Owl                   | <i>Strix seloputo</i>  | 0/0/1                     | 1 y              | Operant conditioning | Van Dijk (1973) |
| Tawny Owl                          | <i>Strix aluco</i>     | 0/0/6                     | 0.5-5.5 y        | Operant conditioning | Van Dijk (1973) |
| White-faced Scops Owl <sup>o</sup> | <i>Otus leucotis</i>   | 0/0/1                     | 1.5 y            | Operant conditioning | Van Dijk (1973) |

<sup>a</sup>Sex includes the number of female, male and unknown (F/M/U designations) individuals studied

<sup>b</sup>Age includes day, week, month and year (d, w, m, y designations) when known; if age was not provided, then body mass (in grams, g) is reported if available

<sup>c</sup>nMLD, or the dorsolateral mesencephalic nucleus, both central and lateral divisions were studied, but most cells were from central division (homologous with the mammalian inferior colliculus); subjects were anesthetized with ketamine and xylazine

<sup>d</sup>Source of Trainer (1946) data was Fay (1988)

<sup>e</sup>More than one bird was tested but data were shown for 1 bird only

<sup>f</sup>CN, or the cochlear nuclei (cells from both magnocellularis and angularis nuclei were studied); subjects were anesthetized with urethane

<sup>g</sup>Includes German Roller and American Singer strains; Belgian Waterslagers were excluded due to a sex-linked genetic mutation related to hearing impairment (Wright et al., 2004)

<sup>h</sup>Not all birds were tested at all frequencies

<sup>i</sup>Median threshold values were reported

<sup>j</sup>The house finch, *Haemorhous mexicanus*, is formerly known as *Carpodacus mexicanus*

<sup>k</sup>Bourke's parrot, *Neopsephotus bourkii*, is formerly known as *Neophema bourkii*

<sup>l</sup>Unpublished data from R. Dooling laboratory; we used fitted curve provided in Dooling (2002)

<sup>m</sup>Although the species was identified as *Tyto alba*, the American barn owl was likely the subject of study, and the International Ornithologists' Union (Gill and Donsker, 2019) identifies this species as *Tyto furcata pratincola*, a species (and subspecies) considered distinct from the Western barn owl (*Tyto alba*)

<sup>n</sup>The International Ornithologists' Union classifies the snowy owl, *Nyctea scandiaca*, as *Bubo scandiacus*

<sup>o</sup>The Northern white-faced owl (*Ptilopsis leucotis*) and the Southern white-faced owl (*P. granti*) were formerly combined into a single species, known as the white-faced scops owl (*Otus leucotis*)

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## Appendix E. Response Evaluation Form

An example of the behavioral response evaluation form used to score bald eagle responses is shown in Figure 45.

| Raptor Behavioral Responses to Acoustic Stimuli |                          |                       |                       |                       |                       |                       |                       |                       |                       |                       |                       |                       |                 |
|---|--------------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------|
| Observer Name: _____                            |                          | Title/Dept.: _____    |                       |                       |                       |                       | Date: _____           |                       |                       |                       |                       |                       |                 |
| Bird ID: _____                                  |                          | Stimulus ID: _____    |                       |                       |                       |                       |                       |                       |                       |                       |                       |                       |                 |
| Trial No.                                       | Bird facing camera (y/n) | Response              |                       |                       |                       | Response Type         |                       |                       |                       |                       |                       |                       |                 |
|   |                          | No Response           | Weak                  | Intermediate          | Strong                | Head Turn             |                       | Head Tilt             | Minor Startle         | Major Startle         | Alerted               | Mouth Opening         | Other (specify) |
|   |                          |                       |                       |                       |                       | L                     | R                     |                       |                       |                       |                       |                       |                 |
| 1   | _____                    | <input type="radio"/> | _____           |
| 2   | _____                    | <input type="radio"/> | _____           |
| 3   | _____                    | <input type="radio"/> | _____           |
| 4   | _____                    | <input type="radio"/> | _____           |
| 5   | _____                    | <input type="radio"/> | _____           |
| 6   | _____                    | <input type="radio"/> | _____           |
| 7   | _____                    | <input type="radio"/> | _____           |
| 8   | _____                    | <input type="radio"/> | _____           |
| 9   | _____                    | <input type="radio"/> | _____           |
| 10  | _____                    | <input type="radio"/> | _____           |
| 11  | _____                    | <input type="radio"/> | _____           |
| 12  | _____                    | <input type="radio"/> | _____           |

Figure 45. Example of the Behavioral Response Evaluation Form used to score the responses of bald eagles to acoustic stimuli.

## Appendix F. Brief Review of Eagle Vocalization Literature

Although limited in scope, the eagle vocalization literature does lay a skeletal foundation for the development of a plan to study alerting responses in eagles to a variety of acoustic signals, and other behavioral studies of bird responses to sound may further inform the effort. It is well known that animals orient in the direction of novel stimuli. Primates, for example, make saccadic eye movements toward visual and auditory stimuli (Jay and Sparks 1987) and owls turn their heads rapidly to orient toward auditory sources (Knudsen *et al.*, 1979). The term “orienting response,” originally coined by I.P. Pavlov (as quoted in Sokolov 1963), however, is not limited to such overt movements of the eyes, head, or body. Orienting responses also include physiological responses such as changes in skin conductance, respiration rate, or heart rate, and pupillary dilation. These findings suggest that consideration of physiological responses to sound may be warranted as we continue trying to more thoroughly understand the alerting response; low priority though.

According to Kimball (2009), vocalizations play a minor role as elements of aggression among bald eagles and aggressive calls were never directed at conspecifics, although the subjects did commonly vocalize when other intruders were present, especially in nesting areas (Verner and Lehman 1982, Eakle *et al.*, 1989). However, according to Yates (1989), territorial behaviors exhibited by adult bald eagles include chasing and displacing other adult conspecifics in addition to vocal production that was directed toward intruding adults. Wing shuddering and vocal production was also observed when birds were perched in the presence of intruding adults.

Steidl (1994), reported that adult (bald) eagles vocalize in (at least) three contexts: (1) early morning or late evening when a pair was observed to concurrently call to one another ("location" advertising calls), (2) as one member of a pair approached the (occupied) nest ("greeting" call), and (3) when disturbed ("alarm" call). The latter was observed when humans or subadult eagles approached a nest occupied with nestlings. Quantitative data are available.

One section from Steidl (1994) of considerable importance in our effort to identify useful alerting acoustic signals was devoted to the question of habituation. Steidl observed a progressive decrease in the behavioral responses of eagles to human activity over the course of the first 24 hours of observation following a continuous disturbance, although birds continued to vocalize at twice their normal rate beyond the 24 hour point following continuous disturbance. Steidl takes the view that the birds exhibit signs of “considerable” stress during this period based on nesting behavior patterns.

Eagles are also vocal immediately preceding nest changes according to Cain (1985). One member of a pair typically initiates an exchange by calling to its mate, and after several vocal exchanges the birds switch positions. Periods when both birds were at the nest usually occurred during nest exchanges, but these periods were brief when considered on a daily basis. Results supporting the view that incubation routines of alternating male and female bouts are accompanied by vocalizations were also observed by Herrick (1933).

One interesting and potentially relevant observation made by Oberholser in 1906 suggested that a bald eagle that he was observing was “wary and difficult of approach, with an eye open for danger and giving suspected things a wide berth....” That being said, this eagle was “surprisingly tame and unsuspecting,” when not “molested.”

When comparing bald and golden eagle calls, Oberholser notes that the call (which one?) of bald eagles is a loud and harsh scream, while the golden's cry "...is a sharp, harsh scream of few notes, and is heard most often during the breeding season." Clark and Wheeler (1983) also point out that the bald eagle is a very vocal bird, especially among conspecifics and that goldens are typically silent (Cramp and Simmons, 1979), while a subset of North American representatives are vociferous near the nest (A. Harmam, personal communication).

As part of a thesis written in 1965, Retfalvi points out that, unlike the view expressed in 1906 by Oberholser, Bent (1937) regarded the repertoire of the bald eagle as "ridiculously weak and insignificant." Retfalvi suggests that there are three call types produced by bald eagles (at least among those studied on the island of San Juan):

- a. A syrinx ("throat") generated "hoarse" call; brief, rapid succession
- b. A "chuckling" sound; like a neighing horse
- c. A gull-like sound typically produced by sub-adult and female birds

Calls were identified by Retfalvi as a:

- 1) "threat" – often uttered on approach of humans or adult and juvenile bald eagles. Consists of the utterance of (a) repeatedly in a harsh manner, followed by (b).
- 2) "mild threat" – uttered on approach of red-tailed hawks and turkey vultures. It consists of a sharp (b) without the final ha-ha-ha sounds.
- 3) an "annoyance" – more often uttered by the female bird, when on guard by the nest alone. Seabirds, crows and passing airplanes induced the call. It consists of (b) with the final ha-ha-ha sounds uttered slowly, often combined with (c).
- 4) "greeting" – expressed on arrival of mate. A highly pitched (b) uttered in a laughing manner. It is often heard during courtship from both sexes. Usually the vocalizing bird draws its head backward until it almost touches the back.
- 5) "hunger call" or gull-call (c) – most often heard from the young, in particular during the last two weeks of family disintegration.

Minimally useful as these descriptors may be, one of our goals might be to characterize calls acquired from captive birds acoustically/objectively.

On May 7, 1962 (love this degree of detail!), Retfalvi recounts an interesting bald eagle experience that, again, suggests that bald eagles are susceptible to, and vocalize in response to, threatening incidents. In response to climbing a tree close to a nest, adult eagles engaged in aggressive, but restrained agitation – darting and thrusting about in the air space around the nest, and of interest to us, vocalizing (strongly) the entire time.

O'Toole *et al.* (1999), studying golden eagle call rates in the post-fledging period, found that mean call rates decreased marginally with age such that the average rate observed in the two week period following fledging was ~ 13 calls/hr and was reduced to ~ 10/hr by two months following fledging (lot of variability and differences were clearly insignificant). O'Toole *et al.* also pointed out that calling rates of young birds were higher in the presence of parents than otherwise and the rate of calling nearly doubled for juveniles when a parent was present, a finding reported by a number of groups (Alonso *et al.*, 1987, Ikeda 1987, Hiraldo *et al.*, 1989, Bustamante 1994). It is generally held that calling by juveniles may signal their location (Ikeda 1987) and may inform parents of the nutritional status of their offspring (Trivers 1974).

Watson (1993) reported on response of bald eagles to helicopter surveys/sounds and found that 57% of agitated birds vocalized.

Becker (2002) reported that bald eagles were flushed from their roost only once in response to loud noise produced by crane operation and only once during a total of 38 pedestrian passes, and were never flushed in response to 28 passenger vehicle passes.

Watson et al (1999) reported that 25% of eagles vocalized in response to pedestrians 75% of the time.

Shea (1970) reported that following prey capture, bald eagles typically produce a short bout of loud vocalizations preceding feeding after flying to a nearby perch carrying the prey (fish) in its talons. Another characteristic vocal period occurred just prior to dawn, when the birds were arriving on the feeding areas. The birds became involved in disputes at that time over favored perching sites. Eagles feeding on the ground appeared to be nervous and would often vocalize when others flew too closely overhead. Vocalizing while on the wing was less frequent, though it sometimes occurred during aerial chases.

One of the most common and distinctive calls of adult birds is a frequency modulated call produced 2 or 3 times with the head held in a horizontal position, followed by a transition to 3 to 5 sharp higher frequency notes with the head in a vertical position; the bird's mouth is held widely open during the call. Immature birds commonly produce a series of sharp, high frequency notes when disturbed. Both mature and immature birds demonstrated a high degree of vocalization variation.

In 1979, David Ellis published a monograph entitled, *Development of Behavior in the Golden Eagle*. Ellis identifies and describes a collection of call types "heard" from blinds close to golden eagle nests.

Call types included:

- Skonks
- Wonks
- Chirps
- Seeir
- Pssa
- Copulation calls
- Rattle-chirps
- Clucks
- Wips
- Hissing

The comparison of call categories with other investigators is complicated by the lack of spectrograms and/or sound files. Ellis does offer the suggestion that the calls labelled as Skonks and Wonks are equivalent to barks described by Yrsaliev (1962). It is likely, then, that the Yrsaliev barks are equivalent to the barks described in our investigation.

Ellis concentrates on call types produced at various stage of development, pointing out that the most common "very young" eaglet call is a "chirp." The call appears to be multifunctional, being produced when the eaglet is either cold, hot, or hungry. His view is that there may be two versions of the call, an utterance described as a monosyllabic whistle produced as either a "drawn-out" or a "soft chattering" whistle produced in groups/clusters.

This call type evolves into the “saair’ as eaglets grow. Saair is a high-pitched call that trails off in a brief low frequency downward sweep. Pssa is characterized as a hunger or feeding call, according to Ellis, that is produced by older, larger eaglets or fledglings. It is also a “drawn-out” whistle (the “ss” element of the call) that ends with a low frequency “a” element (frequency modulated?). Adult females produce the call “sometimes” when approached by an adult male.

A collection of adult call types is also described by Ellis.

The “copulation call” is produced by adult females and is indistinguishable from the adult female “pssa” call. The “skonk” is described as a bark-like call produced by adult females in response to threatening encounters with other birds, birds that may endanger eaglets. The call is often patterned (preceded) with multiple “wonks” and eaglets produce “skonk” calls on some occasions.

“Rattle-chirps” are described as high frequency “chitters” emitted in rapid sequence by distressed eaglets and adults, and are frequently produced in alternation with “clucks”; the clucks are not described. Along with the delivery of carcasses or nesting materials, etc., both adult males and females produce “wonks” in the form of a greeting. They are often combined with “skonks.”

“Wips” are described as brief, high frequency calls (“...of higher frequency than Wonk”) associated with delivery of food to near nest locations. They are produced in series that are occasionally interspersed with wonks.

“Honks,” a “drawn-out low frequency whine” sounding like a goose call, was observed in two captive adults, and was produced when birds were under “severe stress.” In that light, “hissing” was observed (on one occasion I think) during a “wing-spread-flap” performance by an adult when confronted at the nest by an intruder; eaglets also produce this call.

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