REDUCING GILLNET BYCATCH:

SEADUCK UNDERWATER HEARING THRESHOLDS

AND AUDITORY DETERRENT DEVICES

by

Kathleen McGrew

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of the requirements for the degree of Master of Science in Wildlife Ecology

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I would like to dedicate this thesis to my mother, Dr. Maureen Parrott, who fostered scientific curiosity and love of nature in me as a little girl, and who continues to inspire me as an adult. I would not be where I am today without you.

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ABSTRACT

As diving foragers, sea ducks are vulnerable to underwater anthropogenic activities, including naval sonar activity and gillnet fisheries. Bycatch in gillnets is a principle driver of mortality for sea ducks, killing hundreds of thousands of seabirds annually. To reduce gillnet bycatch, I researched the underwater hearing in affected sea duck species to assist with possible development of mitigation strategies via auditory deterrent devices. Additionally, knowledge of underwater acoustic sensitivity is important to current regulatory and management priorities in order to evaluate the impact of noise pollution. To determine underwater hearing sensitivities for diving ducks vulnerable to bycatch, I used psychoacoustic techniques to train captive ducks to respond to sound stimuli. From 2016–2018, I raised and trained long-tailed duck (*Clangula hyemalis*), surf scoter (*Melanitta perspicillata*), and common eider (*Somateria mollissima)* ducklings at Patuxent Wildlife Research Center's breeding facility to participate in underwater hearing tests in the center's dive tanks. I trained ducks using operant conditioning to perform a Go/No-go task, where they reported whether they heard tones of varying frequency and sound pressure level. I performed a logistic regression ($P \leq 0.05$) on the trials of Go/No-go data across the different sound pressure levels to ascertain the likelihood that each individual heard a specific frequency. The predicted 50% threshold for each individual at each frequency was determined from the derived logistic model. Greatest hearing sensitivity was observed at 2.96 kHz for the long-tailed ducks (average predicted threshold of 101.6 ± 0.6 dB) and common eider (predicted threshold of 105.9 dB), while the surf scoters exhibited greatest sensitivity at 1.0 kHz, with an average predicted threshold of 104.8 ± 0.8 dB. Underwater hearing threshold data suggest that these species share a common range of auditory sensitivity, from 1.0–3.0 kHz. Based on the results of this study, sea duck

underwater hearing sensitivities are within range of high intensity noise pollution generated from mid-frequency sonar, small vessel activity, and offshore drilling. The consequences of the overlap between sea duck sensitivity and multiple sources of underwater noise pollution are unknown, but could include disruption of normal biological behavior, masking, and physiological stress. Most commercially available acoustic deterrent devices emit high frequency tones which would not be detected by the species tested in this study; however, a lower frequency pinger in the 2–3 kHz range would fall within sea duck sensitivity and may be a viable option for field testing. While a pinger that emits tones under 3 kHz would be ideal for species with lower frequency sensitivity like surf scoters, tones at this frequency may also fall within sensitives of target fish species, warranting the need for extensive field testing.

Chapter 1

INTRODUCTION

Acoustic energy propagates very efficiently in water, especially compared to electromagnetic, thermal, and light energy, all which are severely attenuated in the underwater environment (Au and Hastings 2008). Due to this efficiency, many aquatic animals have adopted the use of acoustics to perform basic life function tasks such as communication, navigation, and prey detection. However, the effectiveness of sound in the underwater environment also has implications for the magnitude of impact that long-distance noise pollution can have on aquatic animals. Nonetheless, sound may also be used as a tool to alert or deter aquatic animals from dangerous anthropogenic interactions.

Interactions between marine megafauna and commercial fisheries have occurred throughout history and continue to increase due to human population growth and industrialization of the fisheries industry (DeMaster et al. 2001, Lewison et al. 2004). A principal negative interaction between fisheries and marine animals is attributed to bycatch, which typically refers to animals that become hooked, trapped, or entangled in fishing gear (Davies et al. 2009), resulting in mortality or injury to the non-target organism (Biju Kumar and Deepthi 2006). Bycatch has increasingly been recognized as a major driver in marine animal mortality and population declines (Mitchell 1975, Dayton et al. 1995, Read et al. 2006). Marine mammal megafauna and pelagic diving birds are especially vulnerable to exploitation due to iteroparous demographic characteristics (Hunt and Furness 1996, Whitehead et al. 1997, Lewison et al. 2004). Given this, researchers hypothesize the incidental mortality or injury from fisheries operations is a primary influence in the decline of many pelagic bird species (Croxall et al. 2012, Žydelis et al. 2013).

Different species may be more susceptible to bycatch in different fisheries operations. The gillnet fisheries industry has been identified as having the highest bycatch intensity score for air-breathing animals, including seabirds (Lewison et al. 2014). While many studies have addressed the impacts of gillnet fisheries on marine mammals (e.g. Barlow and Cameron 2003, Lewison et al. 2004, Read et al. 2006, Reeves et al. 2013), there is concern that >400,000 seabirds are being killed annually as bycatch across the Atlantic, Pacific, and Baltic Seas (Croxall et al. 2012, Žydelis et al. 2013). Pott and Wiedenfeld (2017) found that 228 seabird species have been recorded interacting with fishing gear and Regular et al. (2013) hypothesized that diving birds are more vulnerable to gillnet bycatch compared to their surface-feeding counterparts. For example, of the estimated 76,000 seabirds in the Baltic Sea that were taken annually as bycatch in gillnet fisheries from 1980–2009, the diving ducks (e.g. long-tailed ducks [*Clangula hyemalis*], common eiders [*Somateria mollissima*], Steller's eiders [*Polysticta stelleri*], and greater scaup [*Aythya marila*]), were the most impacted (Žydelis et al. 2009, Degel et al. 2010). Bellebaum et al. (2013) found that bycatch contributes to monthly losses of 0.81% in long-tailed ducks in the Pomeranian Bay. In the northwest Atlantic, the North American Waterbird Conservation Plan identified fisheries bycatch as a serious threat to at least 17 species of seabirds in U.S. Atlantic waters (Kushlan et al. 2002) with special concern for great shearwaters (*Ardenna* gravis) and common eiders (Merkel 2011, Ellis et al. 2013).

To mitigate fisheries bycatch, several policy advances have occurred. The 1994 amended Marine Mammal Protection Act (MMPA) prohibits "take" (defined as to hunt, harass, capture, or kill) of all marine mammals from U.S. commercial fisheries. Interactions between gillnet fisheries and harbor porpoises (*Phocoena phocoena*) have resulted in a Harbor Porpoise Take Reduction Plan (HPTRP), which sets restrictions on when, where, and how fishing gear is set. The HPTRP is the first TRP to require the use of pingers in the North Atlantic region and provides training for vessel operators and specifications for suitable pingers, including the frequency (10 kHz), sound pressure level (132 dB ± 4 dB re 1 micropascal), and points of attachment (National Oceanic and Atmospheric Administration 2010). Protection is further strengthened if the species is listed under the Endangered Species Act (ESA) (National Marine Fisheries Service 1978, Moore et al. 2009), and the ESA extends to other taxa as well, including seabirds. For example, Washington State gillnet fisheries operators are required to report encounters with marbled murrelets (*Brachyramphus marmoratus*) and retain the bird if recovered alive (Washington Department of Fish and Wildlife 2017). The Migratory Bird Treaty Act (MBTA) of 1918 is the overarching federal legislation aimed specifically at migratory birds; however, whether the boundaries of this Act extend offshore remains up for debate and the U.S. Fish and Wildlife Service (USFWS) has neglected to enforce the Act for seabird bycatch mortality (Manville 2005). While seabirds are not included under the "bycatch" definition of the Magnuson-Stevens Act (MSA, the primary law governing fisheries management and protections for bycatch), a recent framework to begin to address the problem of seabird bycatch has been developed under Section 316 (Benaka et al. 2012). The National Oceanic and Atmospheric Administration

(NOAA) formed the National Seabird Program, which is tasked with mitigating bycatch in U.S. fisheries, and carries out multiple initiatives including the USA International and National Plans of Action for Reducing Incidental Catch of Seabirds in Longline Fisheries. For example, Alaskan fishermen operating vessels longer than 7.9 m and using hook-and-line gear must abide by seabird avoidance requirements, including streamer lines intended to visually deter seabirds (National Oceanic and Atmospheric Administration 2009). However, regulatory legislation and mitigation for gillnets and seabird bycatch has not been extensively developed. The only regulation exists in Washington State sockeye and pink salmon gillnet fisheries which requires night-time closure and installation of a “bird web” to visually alert birds (Washington Department of Fish and Wildlife 2017).

The current preferred technique to mitigate either depredation or bycatch of marine mammals in gillnets is the use of acoustic deterrent devices, or pingers, which emit relatively low intensity tones (<150 dB re 1μPa at 1 meter) at high or ultrasonic frequencies (>10 kHz, with some as high as 160 kHz). Pingers have been designed to emit tones outside the audible range for most fish species, which hear at lower frequencies (Popper and Fay 1993), and alert non-target animals of fishing gear. Optimally, the alert causes non-target animals to exhibit avoidance behaviors and reduces the likelihood of entanglement (Dawson et al. 2013). Many small, economical, battery powered pingers have been developed specifically for reducing bycatch of marine mammals, and multiple commercial brands have come out with custom devices that emit tones within the peak sensitivity range of the taxa of concern (Table 1). Controlled experiments in gillnet fisheries have shown that pingers can be effective in reducing bycatch of multiple marine mammal species (Kraus 1999, Barlow and

Cameron 2003, Burke 2005, Larsen and Krog 2007, Gönener and Bilgin 2009). Confirmation that fish are not hearing or responding to these pingers is provided by reports of consistent lack of negative effect on both target and non-target fish species for multiple commercial pingers (Trippel et al. 1999, Culik et al. 2001, Barlow and Cameron 2003, Gönener and Bilgin 2009). However, because there is little known about the underwater hearing abilities of seabirds, pingers targeting these taxa have not been developed, and few field studies have evaluated the efficacy of existing pingers in reducing seabird bycatch.

Animal hearing can be broken down into categories related to the adaptations involved with the medium that sound travels through. Terrestrial animals have adaptations related to dealing with impendence mismatch between the medium that sound travels through (air), and the fluid-filled inner ear. Wholly aquatic animals have adaptations for hearing underwater, while amphibious animals have adaptations to allow for hearing in both mediums (Wartzok and Ketten 1999). The structure of the avian ear differs from terrestrial mammals in the absence of pinnae and the existence of only a single ossicle compared to the three bony elements found in mammals (Beason 2004). This single ossicle is made up of the columella and the extracolumella, which is comprised of flexible components that allow for effective sound transmission (Saunders et al. 2002). In air, the middle ear acts to correct the impedance-mismatch between the low-impedance medium air to the high-impedance fluid-filled inner ear (Köppl 2015). This impedance-matching mechanism may have adapted to provide protection for the cochlea from drastic pressure changes during flight or underwater diving (Sadé et al. 2008).

In air, avian hearing sensitivities are typically restricted to frequencies below 10 kHz, with most species exhibiting peak sensitivity from 1–4 kHz (Beason 2004, Köppl 2015). For aquatic birds, studies are historically limited, with data existing for mallards (*Anas platyrhynchos*, Trainer 1946, Hill 2017), and black footed penguin (*Spheniscus demersus*, Wever et al. 1969). In more recent years, psychoacoustic and electrophysiological in-air hearing testing have been completed on multiple species of seabirds including the great cormorant (*Phalacrocorax carbo*), surf scoters (*Melanitta perspicillata*), white-winged scoters (*Melanitta fusca)*, black scoters (*Melanitta americana)*, lesser scaup (*Aythya affinis*), harlequin ducks (*Histrionicus histrionicus)*, ruddy ducks (*Oxyura jamaicensis)*, common eiders, red-throated loons (*Gavia stellata*), and northern gannets (*Morus bassanus*) which share a common region of peak sensitivity between 1.0–3.0 kHz (Crowell et al. 2015, 2016; Maxwell et al. 2017). Very limited data exists for underwater sensitivity on diving birds, including great cormorants (Hansen et al 2017) and long-tailed ducks (Therrien 2014), both of which suggested sensitivity in the 1.0–4.0 kHz range. The only pinger study conducted on sea birds tested 1.5 kHz (+/- 1 kHz) frequency pingers in Puget Sound and saw a 50% reduction in common murre (*Uria aalge*) bycatch, but no significant effect on rhinoceros auklet (*Cerorhinca monocerata*) bycatch (Melvin et al. 1999).

Understanding hearing in diving birds is important for the effectiveness of acoustic deterrents to avoid bycatch of birds in gillnets, as well as inform current regulatory and management priorities to evaluate the impact of noise pollution (e.g. offshore energy construction activities and naval sonar activities). My research goal was to use psychoacoustic techniques to determine underwater hearing thresholds for sea ducks, including long-tailed ducks, surf scoters, and common eiders. Additionally, using baseline hearing abilities obtained in the first objective, I determined the potential efficacy of commercially available acoustic deterrent devices to avoid bycatch in gillnet fisheries.

Table 1 Acoustic specifications of a selection of commercially available pingers in 2019.

Product	Target species	Frequency (kHz)	Intensity (dB re 1 μPa at 1 m)	Source
Fishtek Marine: Banana pinger	Whale	3–20 with harmonics	135 ± 3	Fishtekmarine.com
	Porpoise	10 with harmonics	132 ± 3	
Future Oceans "netguard" pinger	Whale	3 ± 0.5	135 ± 4	Futureoceans.com
	Dolphin	8–12	132	
	Dolphin	70	145	
Airmar Gillnet Pinger	Marine mammals (harbor porpoise)	10	132	Airmartechnology.com
STM Products: DDD-03	Dolphin	5–500 Random	165	Stm-products.com

Chapter 2

METHODS

Background

While hearing capabilities of animals can be measured using the evoked potential response of the nervous system via Auditory Brainstem Response (ABR) tests (recorded from the scalp following the auditory stimulation) (Hall 2007), thresholds are often 10–15 dB higher as compared to behavioral methods (Borg 1982, Szymanski et al. 1999, Wolski et al. 2003, Finneran and Houser 2006, Crowell et al. 2016). Thus, researchers widely use behavioral response psychoacoustic tests (Fay 1988) to determine a relationship between a stimulus and a sensory response, with the goal of determining a sensory threshold (Au and Hastings 2008). Past research using this method includes a variety of marine mammal species (Gerstein et al. 1999; Szymanski et al. 1999; Kastelein et al. 2003, 2005; Finneran and Houser 2006) and bird species (Dooling et al. 1971, Maiorana and Schleidt 1972, Dooling and Saunders 1975, Crowell et al. 2016, Maxwell et al. 2017). While researchers consider psychoacoustic methods to be the "gold-standard" of laboratory research for determining hearing abilities in animals (Fay 1988), the drawback is that it often takes an arduous amount of time to train subjects to participate in these behavioral tests, making it difficult to achieve large sample sizes.

Psychoacoustic techniques involve training subjects to respond to test stimuli though a certain behavior (e.g. pushing a lever, Dooling and Okanoya 1995). The animal is expected to respond in a different manner if the stimulus is absent, enabling the observer to estimate detection thresholds. Either classical or operant conditioning is used to conduct these psychophysical studies. In classical conditioning, a conditioned stimulus (e.g. a tone) is presented just prior to an unconditioned stimulus that elicits a physiological response. The unconditioned stimulus is paired repeatedly with the acoustic conditioned stimulus until the acoustic stimulus alone elicits the physiological response. While classical conditioning was used commonly in psychological experiments in the past, operant conditioning has generally been used to train marine mammals (Skinner 2015), the most common subjects for underwater hearing testing. Operant conditioning shapes behaviors through positive reinforcement (usually through a food reward), for responding to a stimulus in a particular "correct" way. There may be a secondary reinforcement, such as a click, that can be used to provide immediate feedback. Incorrect responses to the stimulus result in the absence of positive reinforcement, or a "time out" from the ability to receive a reward (Au and Hastings 2008).

The Yes/No response paradigm is commonly used in psychophysical testing. In the Yes/No response paradigm, there is a single observation interval where the sound stimulus is either present or absent, and the subject has two options to respond including either stimulus-present or stimulus-absent. Thus, if the subject detects the stimulus (yes), it would respond by, for example, touching a specific response target; and if the subject does not detect the stimulus (no), it would respond by touching a different target (Green and Swets 1966). A derivative of the Yes/No response is the Go/No-go response, which is the paradigm used in this study. The subject is trained to respond to the presence of a stimulus (go) by responding with a particular behavior such as touching a target. However, instead of responding in a different manner when a stimulus is not detected, the animal is trained to not respond (no-go), which is thought to be the most straightforward procedure to study acoustic sensitivity (Au and Hastings 2008).

The procedure for a Go/No-go task begins with the subject stationed at an exact location (e.g., at a button or target), orienting toward the direction of the stimulus source, or speaker. Once the stimulus is presented, the subject has a fixed amount of time to respond (go) with the expected behavior (tap a paddle, peck a target, etc.). If no stimulus is detected, the subject is expected to remain at the station for the remainder of the trial, refraining from responding (no-go). There are four distinct outcomes possible with a Go/No-go task (Figure 1): if the stimulus is present, the subject can either respond correctly ("hit") and receive a reward or fail to respond ("miss") and receive no reward. If the stimulus is absent, the subject can either respond as if it perceived a stimulus ("false alarm") or not respond ("correct rejection").

While multiple methods exist for presenting the stimuli to the subject, the two most widely used techniques used for studying acoustic sensitivity include the up/down staircase method and the modified method of constant stimuli (Au and Hastings 2008). In this study, I used a modified method of constant stimuli, where a range of stimulus values are pre-selected before the start of testing, and are not changed based on the outcome of the subject's responses (Dooling and Okanoya 1995, Wolski et al. 2003, Crowell et al. 2016, Maxwell et al. 2017). Using the method of constant stimuli can produce less bias than the up/down staircase method because the subject is unable to anticipate future stimulus levels due to the random presentation order of stimuli (Simpson 1988). Each testing session is comprised of several blocks of equal numbers of trials, with a randomly assigned order of stimulus levels.

Performance accuracy of the subject is recorded as a function of the stimulus values presented, and the threshold is then defined as the stimulus value associated with a given percentage of correct detection, usually the 50% hit rate (Figure 2, Ehrenstein and Ehrenstein 1999, Au and Hastings 2008).

Signal detection theory (SDT) accounts for the inevitable truth that there is noise and interference during any testing event and that detection of a stimulus in the presence of this noise is a decision-making process for the subject. Thus, a threshold value is subject to the individual's motivation and expectation biases, as well as the difference between the signal level and the noise level. For example, if the signal level is much greater than the interfering noise level, the subject will likely make the decision of distinguishing the stimulus relatively easy, resulting in few errors. However, if the signal level is weak, and the noise level is close in comparison, the decision is more difficult and the subject will likely make more errors when faced with a harder distinguishing task (Au and Hastings 2008).

Procedure

I tested the auditory ability of three sea duck species including surf scoters, common eiders, and long-tailed ducks. Specifically, I was able to train and test the hearing of 3 surf scoters (all males), 5 long-tailed ducks (4 male, 1 female), and 1 female common eider. I assumed sex would not affect hearing ability. All birds were raised together at the United States Geological Survey (USGS) Patuxent Wildlife Research Center's (PWRC) captive seabird facility. All ducks were housed in open-air enclosures with 3–7 ducks per pen. Each pen was equipped with a pool of continuously flowing water (circumference 5 m and depth 0.75 m). I fed ducks Mazuri® Sea Duck Diet (21.5% crude protein, 5.0% crude fat, and 4.5% crude fiber).

I gave all birds an identification based on leg band color and hatch year and I identified sex through plumage and inspection of the cloaca for phallus protrusion. All research procedures were approved by the Animal Care and Use Committee at the U.S. Geological Survey Patuxent Wildlife Research Center (Approval #2012-06).

PWRC and the University of Maryland-College Park developed an interactive equipment system to research the behavior and physiology of captive ducks within the PWRC dive tank (2.5 m x 2.2 m x 4 m, Therrien 2014). For auditory behavioral testing, this system included a calibrated underwater speaker (University Sound UW-30, Electro-Voice, Burnsville, MN), an automatic mealworm (reward) dispenser, and two custom-built observation and response targets (Figure 3). The observation and response targets were built of PVC pipe with a pressure-sensitive piezo-electric disk covered in glass that enable the computer to register a pecking response from the bird. Additionally, the targets were equipped with LED lights to signal the bird that a trial had begun. During trials, the observation target sat 33 cm below the surface of the water, with the speaker mounted on a bracket attached to the front wall of the diving tank, 30.5 cm in front of the observation target. The report target and mealworm dispenser were at the surface of the water (Figure 3).

All experimental events were coordinated by Tucker Davis Technologies TDT-RP2.1 and a desktop running specialized MATLAB code (adapted from Prior et al. 2018) which interpreted analogue inputs from the ducks to a set of randomized trials to test frequency response. I used a hydrophone with preamplifier (Teledyne-Reson 4032, Slangerup, Denmark; sensitivity = -170 dB re 1 V/μPa) to calibrate underwater sound stimuli. The hydrophone was positioned directly behind the observation target, at the position where the bird’s ear would be located during stimulus generation.

Customized MATLAB code (Edward Smith, University of Maryland) calibrated the speaker before each auditory sensitivity testing session and produced a set of pre-selected decibel levels within 0.05 dB of the desired level.

I conducted all experimental behavioral training and subsequent data collection trials from June 2016–June 2018. I hand-raised ducklings and began preliminary training a few days after hatch to ensure the ducklings were comfortable with their trainers and the equipment. I trained the ducks using operant conditioning procedures on a Go/No-go task, using mealworms as positive reinforcement (Dooling and Okanoya 1995, Wolski et al. 2003, Skinner 2015, Crowell et al. 2016, Maxwell et al. 2017). I began formal data collection 4–8 months after hatch depending on the individual bird’s ability to progress during training.

To begin a trial, a duck had to dive down and peck a lit observation target continuously until a sound was played. Each time the duck pecked the observation target, the computer generated a random number from 1–10. If the random number generated from the peck was between 7–10, the target lights would stay illuminated and the system would wait for additional pecks. If the random number generated by the peck was between 1–6, the trial would go to completion, with either a tone or a “sham trial”, with the absence of a tone. This randomization accomplished two goals. First, the randomization broke up any behavioral pattern of pecking the observation target and then indiscriminately pecking the report target for a reward. Second, it required the duck to remain stationary at the observation target for an extended period and deliver multiple pecks. This facilitated consistency in the distance from the duck to the speaker when a stimulus was played. If a tone was played, the duck had to peck the response target within 4 sec. If the duck pecked the response target correctly (a hit), a mealworm was delivered as a reward and the target lights were shut off for a random interval between 7–11 sec. If a sound was played and the duck failed to respond (a miss), no mealworm was delivered and the trial would end with the target lights shut off. If the duck pecked the response target in the absence of a sound during a "sham trial" (a false alarm), the target lights were shut off and the duck was put in a 5–10 second "punishment" period with the building lights shut off. I used randomization and computer-coordinated directions to minimize observer bias and misinterpretation of behaviors in the trials. For example, the computer registered when a duck performed a correct behavior and produced the prompt "feed now" to prompt the observer to dispense mealworms.

All training and testing sessions were reward-driven, with birds voluntarily choosing to accomplish tasks. During training sessions, the birds underwent blocks of 10 "training" trials, in randomized order. Seven of the 10 trials played a "training tone" of 135 dB at 1000 Hz, which was selected based on success with previous studies (Therrien 2014) as well as observation of the birds reacting to the tone in a way that suggested the frequency and decibel combination of this tone was well above their hearing threshold. The remaining 3 trials were "sham trials" with no tone played, designed to confirm the bird's understanding of the task. Training sessions consisted of as many as 10 trial blocks with the length of sessions depending on individual's willingness to participate on any given day. "False alarm" rates were calculated from each bird's incorrect response rate during "sham trials". To begin formal testing, I required ducks to have a hit rate of $\geq$ 80% (and a false alarm rate $\leq$ 20%) during the training phase. Due to the complicated nature of the task, I conducted intermittent training sessions in between sessions of data collection.

The underwater auditory stimulus was a 1000 ms sinusoidal pulse with rise and fall times of 1 ms. I chose a single pulse to accommodate the very brief period the duck remains stationary at the observation target while diving underwater. Prior to testing, I used an oscilloscope (SDS5032E, Owon, Zhangzhou, China) to visualize peak output voltage of the hydrophone for each intended frequency to be tested (1.0 kHz, 2.0 kHz, 3.0 kHz, 4.0 kHz). This visualization showed some possible constructive and destructive interference around the two higher frequencies of 3.0 and 4.0 kHz. This interference occurs when two sound waves are either in phase or out of phase with one another, and can occur through reflectance off the walls of a closed acoustic environment when the path-length difference corresponds with a specific proportion of wavelengths. I adjusted these two frequencies slightly (within ± 50 Hz of the intended frequency) to minimize the possible interference that I observed through the oscilloscope. Therefore, I measured hearing sensitivity for frequencies of 0.5 kHz, 1.0 kHz, 2.0 kHz, 2.96 kHz, and 4.02 kHz. Each testing session consisted of tones played at a single frequency and a pre-selected set of 7 randomly played decibel levels including 95, 105, 115, 125, 135, 135, 135 dB for 0.5 kHz, 4.02 kHz and 85, 95, 105, 115, 125, 135, 135 dB for 1.0 kHz, 2.0 kHz, and 2.96 kHz. I played no tones >135 dB re 1 μPa to avoid speaker distortion and hearing damage. For all frequencies, the highest decibel level (135 dB) was repeated (2 times for 1.0 kHz, 2.0 kHz, and 2.96 kHz and 3 times for 0.5 kHz, 4.02 kHz) to provide several opportunities for food rewards during testing sessions. This helped to ensure the birds could receive enough food rewards and remain motivated during testing at frequencies they did not hear as well. I randomly mixed the 3 “sham trials” among the 7 varied tones, creating a 10-

trial block session. After a session was completed, the computer generated a new random order of the pre-selected dB levels for the next testing session.

I defined "threshold" as the sound pressure level (SPL) corresponding to a 50% hit rate (Au and Hastings 2008). I performed a logistic regression ($P \leq 0.05$, IBM Corporation 2018) on the trials of Go/No-go data across the different sound pressure levels to ascertain the likelihood that each individual heard a specific frequency. The predicted 50% threshold for each individual at each frequency was determined from the derived logistic model. I automatically deleted 1) any 10-trial testing session with ≥ 2 false alarms, or 2) any testing blocks or entire sessions with > 20% false alarms or where any disturbance (e.g. occasional audible construction activity occurring near the building) affected the birds' normal behavior.

I used univariate repeated measures analysis of variances (ANOVAs) to compare thresholds across species and frequencies. Tests were considered significant at $P \leq 0.05$ and analyses were performed using JMP® (JMP® Version 14.0.0. SAS Institute Inc., Cary, NC, 1989-2019).

Figure 1 The binary decision matrix showing the four possible responses in a Go/No-go task: two correct responses (hit, correct rejection) and two incorrect responses (miss, false alarm).

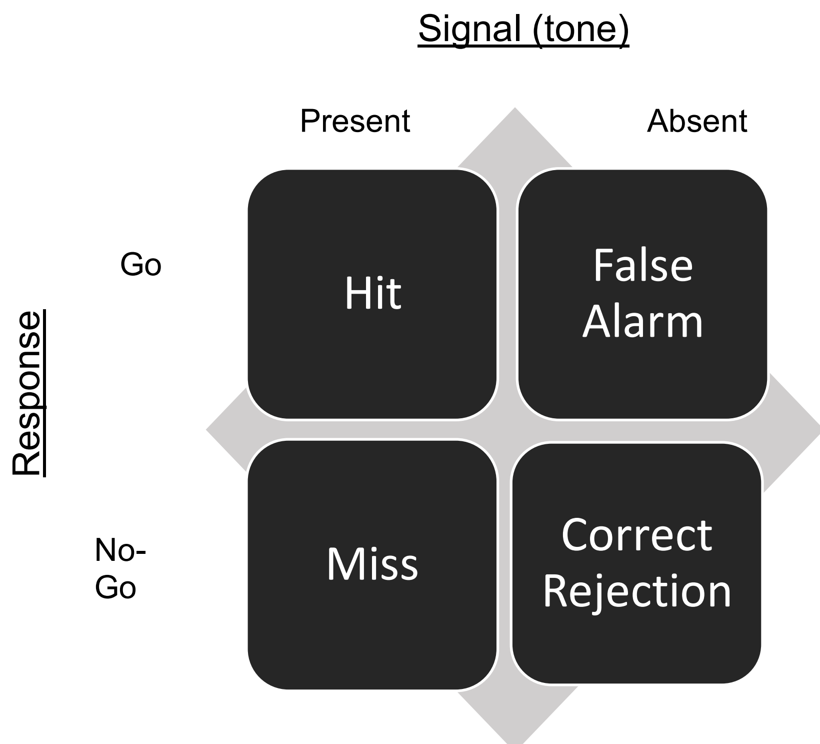


Figure 2 Psychometric function showing the relationship between the percentage of times that an individual perceived a stimulus and the intensity of the stimulus. The threshold, shown as the dotted line, corresponds with the intensity that that stimulus is detected by the subject 50% of the time (Ehrenstein and Ehrenstein 1999).

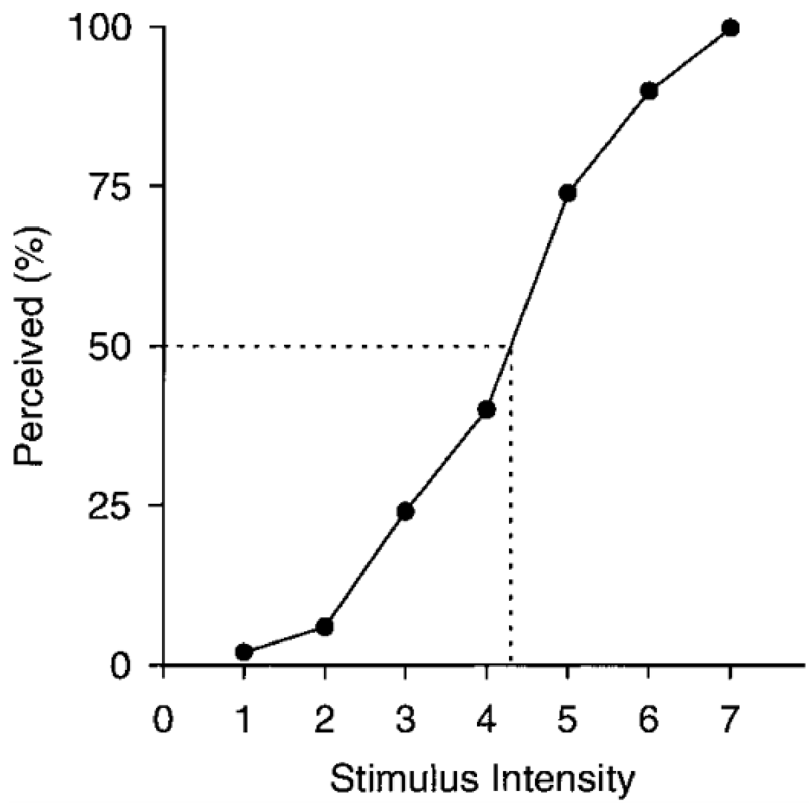
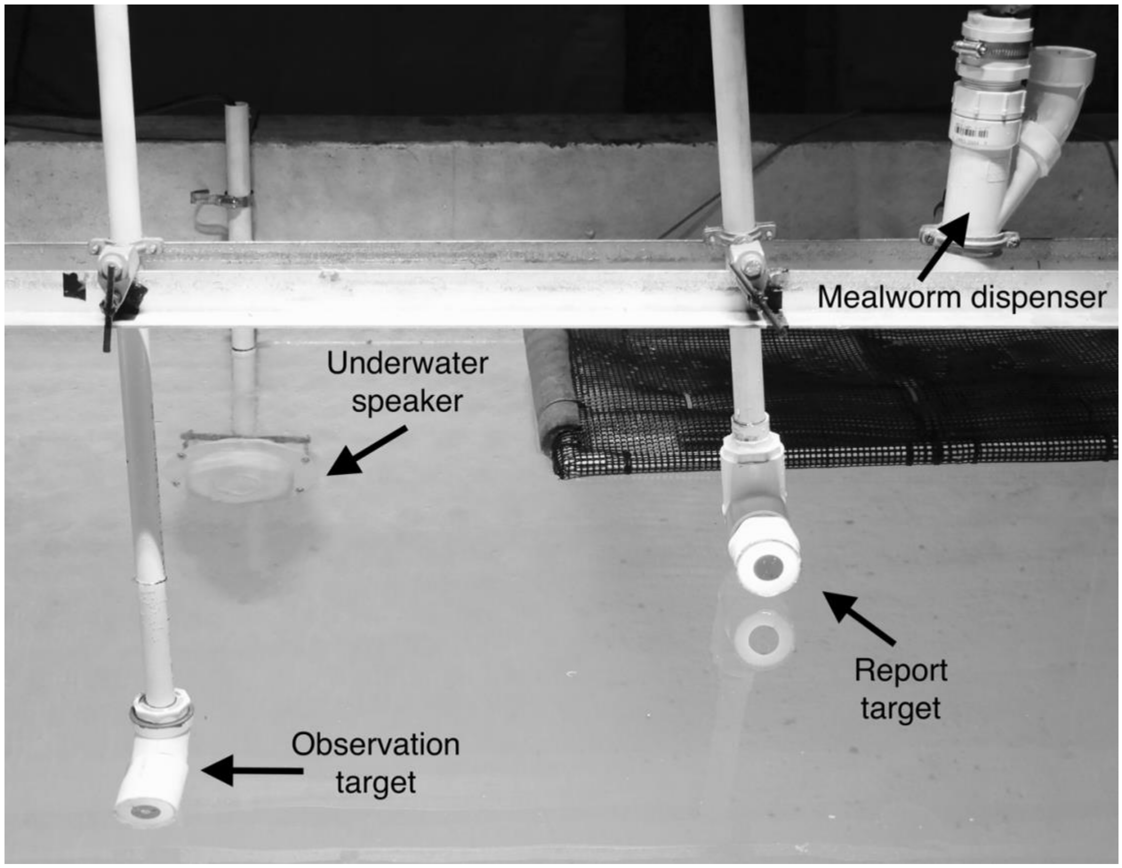


Figure 3 Equipment design for psychoacoustic Go/No-go testing of long-tailed ducks (*Clangula hyemalis)*, surf scoters (*Melanitta perspicillata*), and common eiders (*Somateria mollissima*) in the dive tank facility at Patuxent Wildlife Research Center, Laurel, Maryland, USA 2016–2018.



Chapter 3

RESULTS

I obtained complete audiograms for 8 individuals across 3 species including 3 surf scoters, 4 long-tailed ducks, and one common eider (Table 2). A complete audiogram included threshold data at five frequencies including 0.50 kHz, 1.00 kHz, 2.00 kHz, 2.96 kHz, and 4.02 kHz. For one additional long-tailed duck, I was able to obtain threshold data at three of the five frequencies. I discarded <15% of sessions for each bird because of a false alarm rate >20%.

Long-tailed ducks

Four long-tailed ducks had complete audiograms. Although incomplete, I included a 5^{th} audiogram (LTDU-Pink) where I collected 180 trials for 1.0 kHz and 2.0 kHz, 100 trials at 0.5 kHz, and no data for 2.96 and 4.02 kHz. For illustrative purposes, psychometric functions for all five long-tailed ducks at 2.0 kHz are shown (Figure 4). In this figure, each point represents an individual long-tailed duck's average hit rate taken across all 30 trials per sound pressure level at 2.0 kHz. At this frequency, two stimulus levels (85 and 95 dB) were well below threshold, one was slightly above threshold (105 dB), and three stimulus levels appeared to be well above threshold, the loudest two (125 and 135 dB) corresponding with close to 100% hit rates for each bird. For the data collected at 2.0 kHz (Figure 4), the logistic regression models for each bird predicted that they heard the tone 50% of the time at 107.4 dB for LTDU-White, 108.8 dB for LTDU-Pink, 105.0 dB for LTDU-Blue, 104.2 dB for LTDU-Green, and 103.8 dB for LTDU-Orange. The logistic regression models for all individuals, frequencies, and sound pressure levels were statistically significant $X^2_1 > 40.91$, $P < 0.001$ (Table 3). The logistic models explained 33.0–72.9% (Nagelkerke

R^2) of the variance in individual response to the Go/No-Go task and correctly classified 74.0–90.6% of cases.

I compiled predicted threshold data for all individuals at each frequency to create an average audiogram (Figure 5), which showed that the long-tailed ducks exhibited greatest sensitivity at 2.96 kHz, with an average predicted threshold of 101.6 ± 0.6 dB. The high-frequency roll-off was steeper than the low frequency roll-off, with average predicted threshold levels of 110 ± 1 dB for 4.02 kHz, and 106 ± 1 dB for 2.0 kHz (Figure 5*a*). The average predicted threshold was 106 ± 2 dB at 1.0 kHz and 116 ± 1 dB at 0.5 kHz (Figure 5*a*). I discarded <15% of long-tailed duck sessions because of false alarm rates >20% (10% for LTDU-Blue, 12% for LTDU-Green, 11% for LTDU-Pink, 10% for LTDU-Orange, and 8% for LTDU-White).

Surf Scoters

The logistic regression models for all individuals, frequencies, and sound pressure levels were statistically significant $X^2_1 > 59.46$, $P < 0.001$ (Table 3). The models explained 44.0–89.2% (Nagelkerke R^2) of the variance in individual response to the Go/No-Go task and correctly classified 79.3–88.9% of cases. The models suggested that all three surf scoters exhibited greatest sensitivity at 1.0 kHz, with an average predicted threshold of 104.8 ± 0.8 dB (Figure 6*a*). The low-frequency roll off was steeper than the high frequency roll-off, with average predicted threshold levels of 115 ± 1 dB for 500 Hz and 109 ± 2 dB at 2.0 kHz. The average predicted threshold was 114 ± 2 dB at 2.96 kHz, and 122.8 ± 0.6 dB at 4.02 kHz. I discarded <15% of sessions because of false alarm rates >20% (13% for SUSC-White, 5% for SUSC-Yellow, and 9% for SUSC-Green).

Common Eider

The logistic regression models for all frequencies, and sound pressure levels were statistically significant for this individual $X^2_1 > 93.65$, $P < 0.001$ (Table 3). The models explained 55.2–70.7% (Nagelkerke R^2) of the variance in individual response to the Go/No-Go task and correctly classified 84.0–87.8% of cases. COEI-Red's predicted threshold values were compiled into an audiogram, which shows a flat curve around the area of greatest sensitivity between 1.0–3.0 kHz (Figure 7). I observed greatest sensitivity at 2.96 kHz with a predicted threshold of 105.9 dB. COEI-Red exhibited similar thresholds at 1.0 kHz and 2.0 kHz with thresholds of 106.5 and 106.4, respectively. A steep low frequency roll-off occurs at 0.50 kHz, with a threshold of 118.7 dB, and I observed a threshold of 108.0 at 4.02 kHz. I discarded 3% of sessions due to false alarm rates >20%.

Cross-species comparison

The audiograms for the common eider, long-tailed ducks, and surf scoters were U-shaped (Figure 5*b*, 6*b*, 7). However, unlike the average surf scoter audiogram, that showed a distinctive dip at 1.0 kHz, the average long-tailed duck and common eider audiograms showed similar sensitivities from 1.0–2.96 kHz. Sensitivity for all three species peaked between 1.00–2.96 kHz, with a steep low-frequency roll-off of approximately 10 dB per octave under 1.0 kHz. The average surf scoter audiogram showed the highest thresholds overall. Additionally, the average surf scoter audiogram had the steepest high-frequency roll-off of approximately 10 dB per octave above 2.0 kHz. The average long-tailed duck and common eider audiogram showed similarity at all frequencies, though the long-tailed duck audiogram showed a greater threshold dip for their peak hearing frequency at 2.96 kHz. There were significant effects of frequency ($F_{4, 21.5} = 39.54$, $P < 0.01$) and the interaction of species and frequency ($F_{8, 21.5} = 12.71$, $P < 0.01$). There were no significant effects of species alone ($F_{2, 5.4} = 4.92$, $P = 0.06$). All three species exhibited similar thresholds at lower frequencies (0.5 kHz and 1.0 kHz).

Table 2 Study subjects of underwater auditory testing of long-tailed ducks (*Clangula hyemalis)*, surf scoters (*Melanitta perspicillata*), and common eiders (*Somateria mollissima*) at Patuxent Wildlife Research Center, Laurel, Maryland, USA 2016–2018.

Species	Hatch year	Individual ID	Sex	Audiogram
Surf scoter	2016	Yellow	Male	Complete
		Green	Male	Complete
		White	Male	Complete
Long-tailed duck	2016	White	Male	Complete
		Pink	Male	Complete data for 1.0 kHz and 2.0 kHz, limited data for 0.5 kHz. No data for 2.96 kHz and 4.02 kHz.
	2017	Orange	Male	Complete
		Blue	Male	Complete
		Green	Female	Complete
Common Eider	2017	Red	Female	Complete

Table 3 Results of logistic regression performed to determine the effects of sound pressure level on the likelihood that long-tailed ducks (*Clangula hyemalis)*, surf scoters (*Melanitta perspicillata*), and common eiders (*Somateria mollissima*) detect tones at varying frequency at Patuxent Wildlife Research Center, Laurel, Maryland, USA 2016–2018.

Species	ID	Frequency	N trials	Nagelkerke R^2	Correctly classified cases (%)	X^2	P	Predicted 50% threshold
Long-tailed duck	White-16	0.50	150	0.63	88.0	94.96	<0.001	112.56
		1.00	180	0.73	90.6	135.72	<0.001	103.47
		2.00	180	0.68	86.7	126.97	<0.001	107.36
		2.96	180	0.65	86.1	115.46	<0.001	103.44
		4.02	150	0.52	81.3	67.81	<0.001	106.17
	Pink-16	0.50	100	0.52	81.0	49.77	<0.001	120.11
		1.00	180	0.64	85.0	118.60	<0.001	111.76
		2.00	180	0.58	78.9	102.49	<0.001	108.82
		2.96	0	-	-	-	-	-
		4.02	0	-	-	-	-	-
	Blue-17	0.50	150	0.62	85.3	91.75	<0.001	114.55
		1.00	180	0.66	89.4	117.93	<0.001	103.79
		2.00	180	0.55	84.4	92.66	<0.001	105.02
		2.96	180	0.50	82.8	76.79	<0.001	100.46
		4.02	150	0.33	76.7	40.91	<0.001	110.78
	Green-17	0.50	150	0.50	80.0	70.07	<0.001	116.84
		1.00	180	0.63	85.0	112.50	<0.001	106.41
		2.00	180	0.58	83.9	97.61	<0.001	104.18
		2.96	180	0.61	85.6	103.57	<0.001	100.63
		4.02	150	0.40	76.7	51.58	<0.001	113.25
	Orange-17	0.50	150	0.35	74.0	44.71	<0.001	117.41
		1.00	180	0.54	81.7	90.08	<0.001	104.40
		2.00	180	0.66	88.3	117.93	<0.001	103.79
		2.96	180	0.59	87.2	98.12	<0.001	101.80
		4.02	150	0.51	80.0	68.52	<0.001	109.73
	Average	0.50	700					116.29 ± SE 1.29

		1.00	900					105.97 ± SE 1.54
		2.00	900					105.84 + SE 0.97
		2.96	720					101.58 ± SE 0.62
		4.02	600					109.98 ± SE 1.31
Surf Scoter	White-16	0.50	150	0.49	79.3	67.86	<0.001	116.61
		1.00	180	0.46	80.6	73.64	<0.001	106.22
		2.00	180	0.61	84.4	108.77	<0.001	112.49
		2.96	180	0.69	88.9	130.46	<0.001	116.13
		4.02	150	0.44	80.0	59.46	<0.001	124.05
	Yellow-16	0.50	150	0.62	85.3	93.19	<0.001	113.48
		1.00	180	0.63	86.1	108.85	<0.001	103.37
		2.00	180	0.62	80.0	88.31	<0.001	105.79
		2.96	180	0.71	87.8	135.02	<0.001	109.67
		4.02	150	0.58	84.0	85.45	<0.001	122.11
	Green-16	0.50	150	0.89	82.7	92.21	<0.001	116.29
		1.00	180	0.60	83.3	103.06	<0.001	104.76
		2.00	180	0.56	83.9	97.25	<0.001	110.55
		2.96	180	0.59	86.7	104.69	<0.001	116.71
		4.02	150	0.61	85.3	89.90	<0.001	122.31
	Average	0.50	450					115.46 ± SE 0.99
		1.00	540					104.78 + SE 0.82
		2.00	540					109.61 ± SE 1.99
		2.96	540					114.17 ± SE 2.26
		4.02	450					122.82 ± SE 0.61
Common Eider	White-16	0.50	150	0.71	84.0	113.33	<0.001	118.68
		1.00	180	0.55	86.1	93.99	<0.001	106.45
		2.00	180	0.55	87.8	93.65	<0.001	106.36
		2.96	180	0.62	86.1	109.10	<0.001	105.91
		4.02	150	0.67	86.7	98.46	<0.001	108.00

Figure 4 Psychometric functions at 2.0 kHz for five long-tailed ducks (*Clangula hyemalis*) tested at Patuxent Wildlife Research Center, Laurel, Maryland, USA from 2016–2018, identified by hatch year and leg color band. Each point represents the average of 30 trials. Logistic regression was performed to generate an expected threshold for each individual, defined as the stimulus level that corresponds with a 50% correct rate.

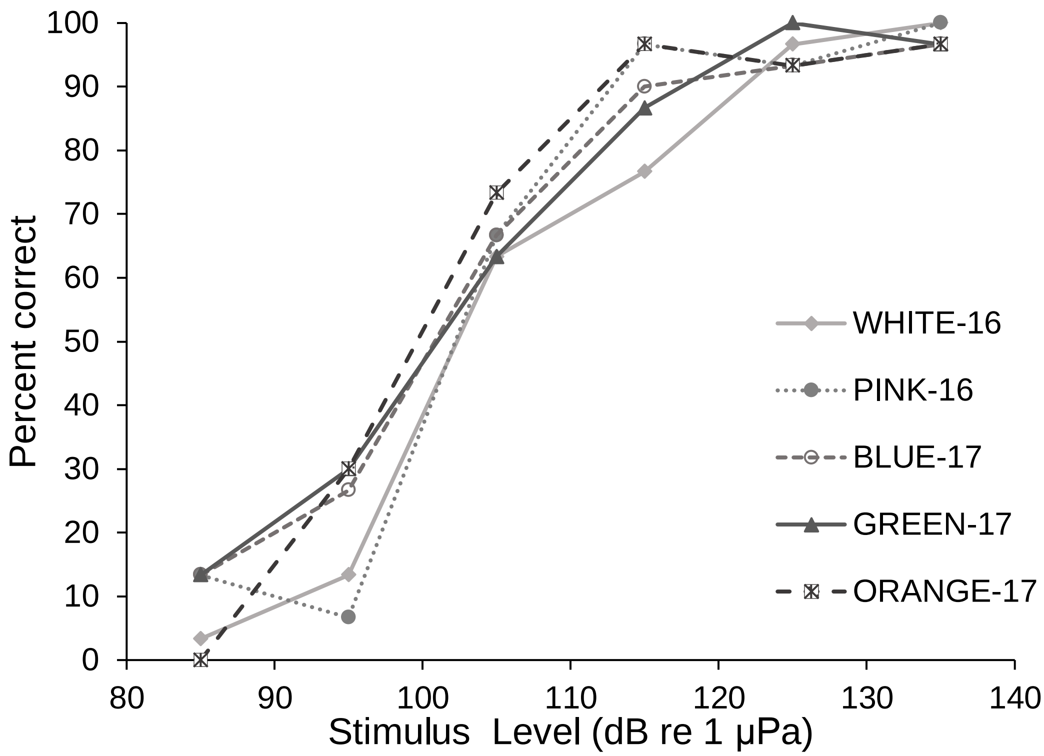


Figure 5 **a)** Audiograms for long-tailed ducks (*Clangula hyemalis*) tested at Patuxent Wildlife Research Center, Laurel, Maryland, USA from 2016–2018, (n=5 for 0.5 kHz, 1.0 kHz, and 2.0 kHz; n=4 for 2.96 kHz and 4.02 kHz), with predicted threshold corresponding to a hit rate of 50%. Each predicted threshold point was generated from logistic regression using 100-180 trials of data, except for Pink-16. **b)** Average long-tailed duck audiograms. Error bars represent ± 1 standard deviation.

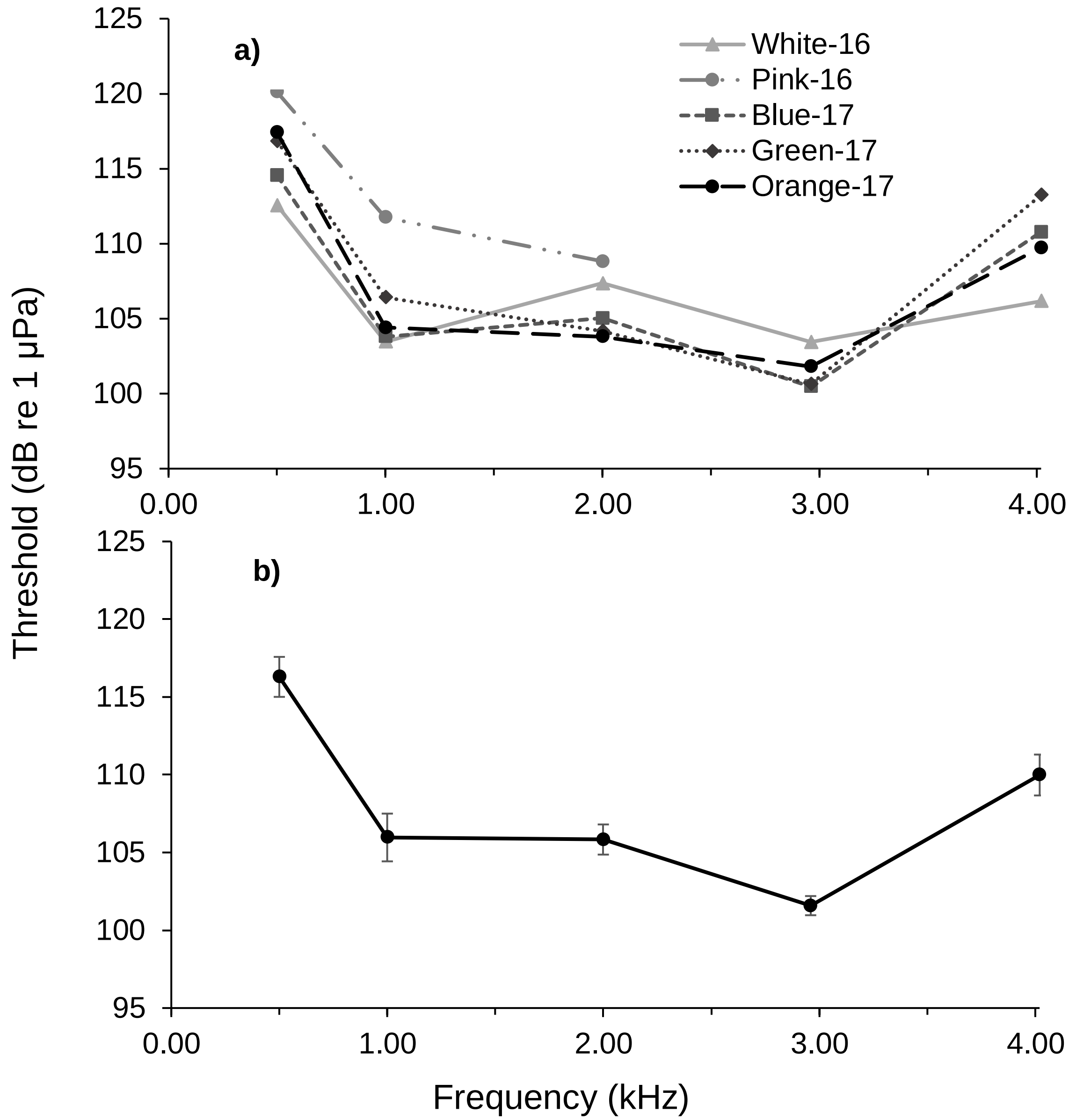


Figure 6 **a)** Audiograms for all three surf scoters (*Melanitta perspicillata*) tested at Patuxent Wildlife Research Center, Laurel, Maryland, USA from 2016–2018, with predicted threshold corresponding to a hit rate of 50%. Each predicted threshold point was generated from logistic regression using 150–180 trials of data. **b)** Average audiograms for three surf scoters. Error bars represent ±1 standard deviation.

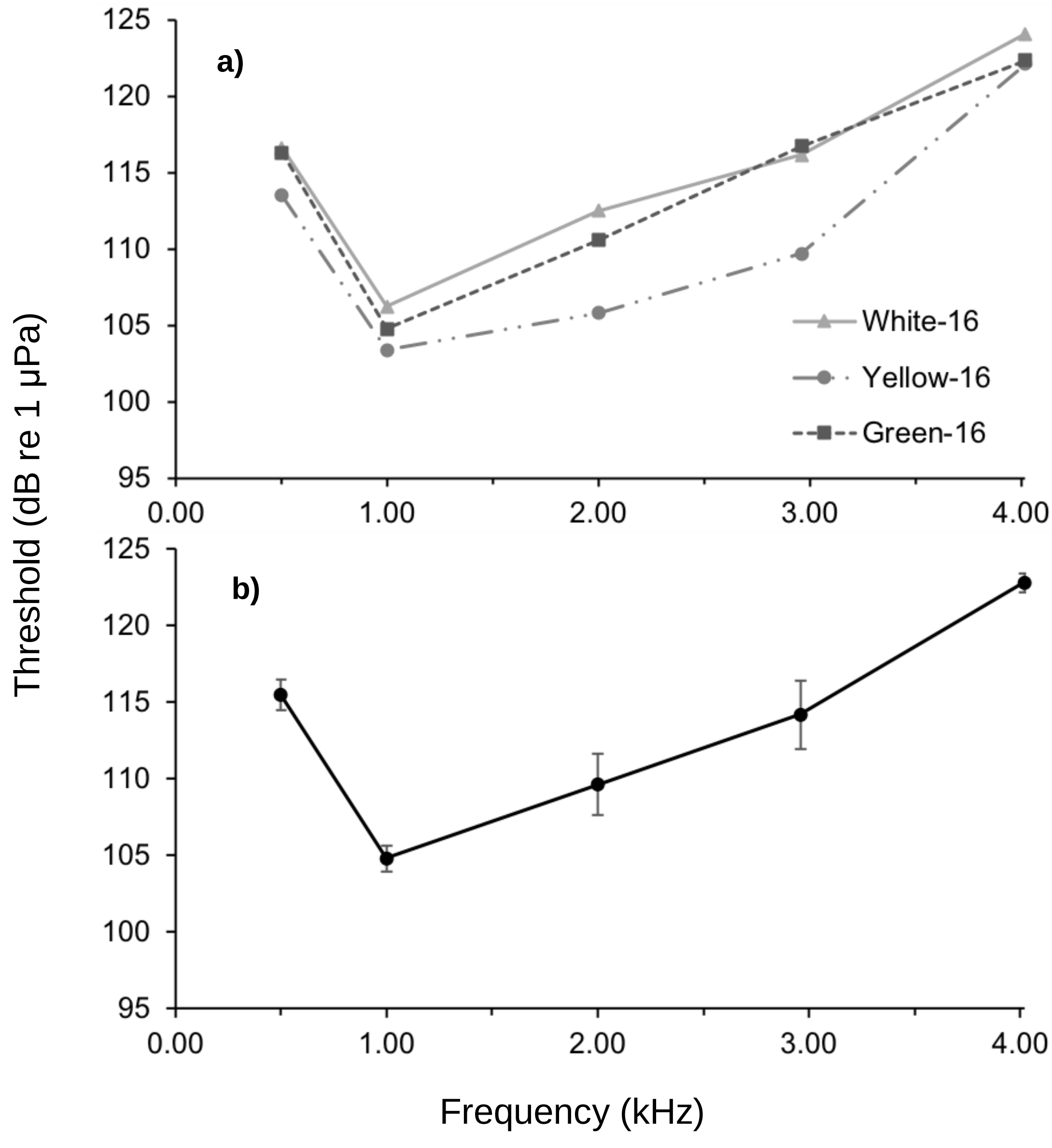
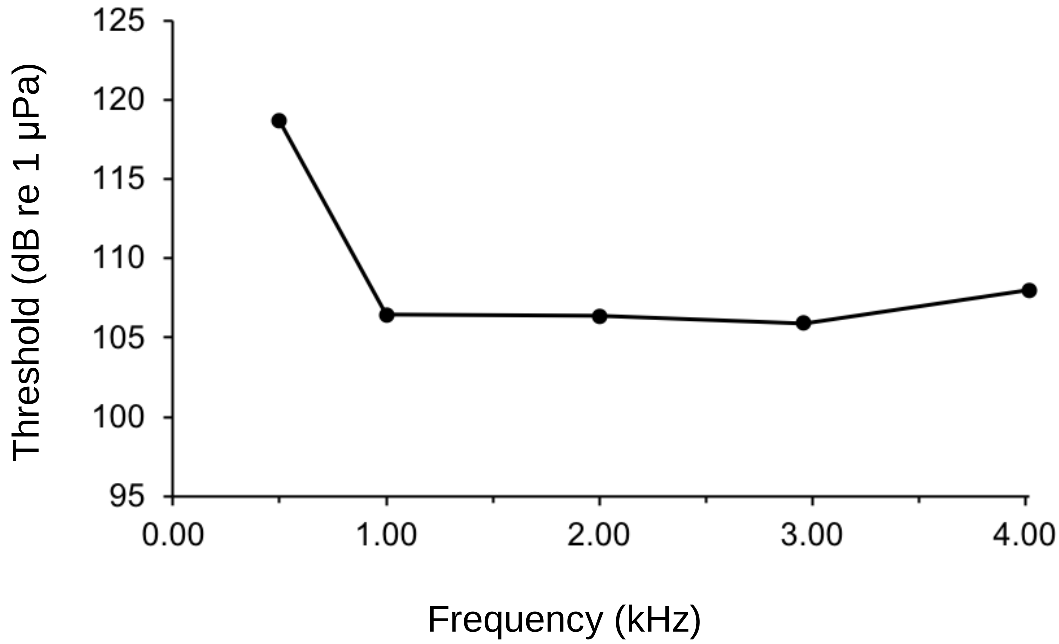


Figure 7 The audiogram for one common eider (*Somateria mollissima*) tested at Patuxent Wildlife Research Center, Laurel, Maryland, USA, from 2017–2018. Predicted threshold corresponds to a hit rate of 50%. Each predicted threshold point was generated from logistic regression using 150–180 trials of data.



Chapter 4

DISCUSSION

All of the complete behavioral audiograms I obtained for my study birds were characteristically U-shaped, with sensitivity peaking between 1.00–2.96 kHz for the three species. This is in line with the only published study that produced underwater hearing threshold estimates in an avian species, which found that great cormorants have a greatest sensitivity at 2 kHz, with a threshold of 71 dB re 1 μPa (Hansen et al. 2017). Compared to the great cormorant, the duck species I tested had higher threshold levels at their most sensitive frequencies. The long-tailed ducks exhibited the lowest threshold of the diving ducks tested, with a threshold of 101.6 ± 0.6 dB re 1 μPa at 2960 Hz, more than 25 dB higher than the great cormorant. These results may indicate that the underwater hearing abilities of sea ducks may not be as specialized as other species of diving birds, like the great cormorant. However, it may be difficult to compare the results of this study with those of Hansen et al. (2017), given the difference in depth of the testing set-up. My setup included the speaker and target positioned at a depth of 33 cm below the surface of the water, while Hansen et al. (2017) conducted testing at a depth of 15 cm. At shallow depths, reflection off the surface of the water affects acoustic propagation that may impact the signal that the subject will receive (Au and Hastings, 2008). The audiograms for the long-tailed ducks, surf scoters, and common eider I tested had significant differences across frequencies, and the interaction between species and frequency. The significant impact of frequency is as expected, given the U-shaped characteristics of each species audiogram.

Due to the complicated nature of the hearing test, and the need for replication of testing at each frequency, data collection for each individual took extensive periods of time. Individual differences in birds resulted in varying timelines of data collection from one bird to the next. For instance, my data collection for COEI-Red commenced just 4 months after hatch, and was completed 5 months later. This bird had only a minor phase of "disinterest" where little to no data collection occurred for about a month, but otherwise needed fewer training sessions compared to some of the other subjects. On the other hand, data collection for LTDU-White took 13 months that included a period of ~5 months where no data was collected due to illness and lack of participation. Each individual's relatively unique timeline of testing could create variability in threshold value. However, avian basilar papilla is known to continuously regenerate hair cells, meaning that age-related threshold shifts are unlikely to occur, unlike the age-related hearing loss observed in mammals (Köppl, 2015). Nonetheless, the time of year I tested the birds, and the associated levels of sex hormones at the time of testing, could impact hearing thresholds. In a study done with Gambel's white-crowned sparrows (*Zonotrichia leucophrys*), Caras et al. (2010) found that birds housed under breeding conditions had higher ABR thresholds compared with those housed in non-breeding conditions.

A closed tank environment poses challenges to acoustic testing and limited the range of frequencies I was able to collect data at. Low frequency signals produce standing waves when their wavelengths are equal to the dimensions of the tank, altering the intensity of an acoustic field (Au and Hastings, 2008). I was unable to test at frequencies lower than 0.50 kHz due to this restriction, but future studies may explore seabird sensitivities at lower frequencies in a larger tank or more open acoustic environment. An additional limitation to this study is that it is very difficult to achieve consistent ear placement for each individual during trials. The testing setup required the subject to continuously peck the observation target as a way to require that the individual remains relatively stationary in front of the speaker, in an attempt to standardize the location of the ears when the sound stimuli was played. However, each individual may approach the target differently while diving; either from a different side or with a different speed, and may lead to discrepancies in the location of the ears. Future studies should examine ways to better standardize the location of the subjects' ears to the speaker, possibly through using a funnel device that the animal would stick its head through to access the target.

The baseline underwater hearing sensitivity data that I obtained for each species can further our understanding of how these animals interact with acoustic energy in the underwater environment. Acoustic energy propagates very efficiently in water, especially compared to electromagnetic, thermal, and light energy; all of which attenuate severely in the underwater environment (Au and Hastings 2008). Due to this efficiency, many aquatic animals have adopted the use of acoustics to perform basic life function tasks such as communication, navigation, and prey detection.

There is little information known about whether diving birds use sound underwater; however, there are many reasons to hypothesize that auditory cues may be important in underwater orientation, communication, and/or foraging. Some penguin species exhibit high occurrences of dives at night when visibility is low and visual detection may be less important, indicating a possible reliance on different sensory cues to detect prey (Croxall et al. 1988). Furthermore, evidence of adaptations for diving can be seen in the structure of diving birds' ear. Cavernous tissues protect the middle and external ear of king penguins (*Aptenodytes patagonicus*) on deep dives by a mechanism that increases water pressure, similar to the hearing apparatus found in marine mammals (Sadé et al. 2008). Unfortunately, underwater communication by seabirds remains an unanswered question. The only documentation of underwater vocalization of a diving bird is of a single macaroni penguin (*Eudyptes chrysolophus*) recorded at the Moscow Zoo (Markov 1977). Nonetheless, diving birds may use gradations in the underwater soundscape to locate suitable foraging areas. During the winter months, diving birds such as long-tailed ducks and surf scoters have been observed foraging on oyster reefs, which provide habitat for many important prey items, including mollusks, crustaceans, and fishes (Perry et al. 2009). These populations of species that inhabit the reef generate a distinct soundscape composed of more sound in the ~2–20 kHz range that can be distinguished from lower frequency adjacent soft-bottom habitats (Lillis et al. 2016). My results suggest that these study species may have the ability to detect this reef soundscape, which overlaps with the range of peak hearing sensitivity for these species. If seabird species do indeed use their underwater hearing abilities to locate foraging areas, anthropogenic noise in the underwater environment may interfere with this vital process.

However, the effectiveness of sound in the underwater environment also has implications for the magnitude of impact that long-distance noise pollution can have on marine animals. Much of the attention has been directed at understanding the physiological and behavioral consequences of high-intensity short-term exposures, such as pile driving for offshore wind farms or marine seismic surveys, which are considered to produce the most intense anthropogenic ocean noise (Southall et al. 2009). Studies have revealed effects of seismic surveys on marine mammals, including hearing threshold shifts and auditory damage, altered communication and temporary displacement (Gordon et al. 2003, Di Iorio and Clark 2010, Castellote et al. 2012). While most of the literature focuses on marine mammals, impacts on other taxa have been examined, including fish, invertebrates, and more recently, seabirds. Pichegru et al. (2017) examined the effects of seismic survey activities on African penguins (*Spheniscus demersus)*, finding the first record of avoidance behavior by a seabird to anthropogenic noises in the ocean environment. Underwater noise generated from shipping is increasingly recognized as a noteworthy pollutant, capable of impacting marine fauna worldwide (Clark et al. 2009, Williams et al. 2015). Commercial shipping contributes to low frequency noise pollution between 0.005–0.500 kHz (Hildebrand 2004), which is likely outside the sensitivities of the sea duck species tested, who experienced steep drop-offs in sensitivity at lower frequencies. However, small powerboats have been documented as having peak spectral density levels between 0.350–1.2 kHz (Barlett and Wilson 2002), a slightly higher frequency signature that has partial overlap with sea duck sensitivity. Mid-frequency (1–10 kHz) military sonar has been linked to mass strandings and cetacean mortality (Jepson et al. 2003, Cox et al. 2006, D'Amico et al. 2009). Peak underwater hearing frequencies for the three species of tested sea ducks (1–3 kHz) fell directly in this range of mid-frequency sonar. Additionally, ships drilling for oil and gas produce broadband high intensity underwater noise between 0.010–10 kHz, overlapping with sea duck sensitivities with a sound pressure level of about 190 dB re 1 μPa at 1 m (Richardson 1995).

The consequences of the overlap between sea duck sensitivities and multiple sources of high intensity underwater noise are largely unknown. Hawkins and Popper

(2016) outlined the range of potential effects of a high intensity sound on fish at different distances with increasing behavioral responses, masking (i.e. the difficulty of an animal to detect biological sounds against a noisy background), impaired hearing, physical and physiological effects, and finally death as they existed closer to the source. Behavioral responses can occur at low sound levels, meaning that effects may be widespread from a single source (Popper et al. 2014). Adverse behavioral responses can include displacement from high quality habitat and changes in movement patterns, and can result in negative impacts on growth, survival, and reproduction (Hawkins and Popper 2016).

In addition to identifying areas of overlap between sea duck hearing sensitivity and sources of underwater noise pollution, these baseline hearing data may be used to inform the development of pingers intended to keep vulnerable animals away from dangerous anthropogenic interactions. When developing a pinger with the goal of deterring underwater animals, possible effects on non-target species must also be evaluated. For gillnet fisheries, it is vital that any deterrent device does not compromise catch rates of fish. Ideally, a deterrent device would minimize damage and predation caused by unwanted interactions with predators, thereby enhancing catch rates.

Multiple field studies have sought to determine whether acoustic deterrent devices effect the catch rates of target fish species (Trippel et al. 1999, Culik et al. 2001, Buscaino et al. 2009, Gönener and Özdemir 2012). Pingers on the market as of 2019 typically use high frequencies to target marine mammals, which is thought to be outside the range for most fish species, which hear at lower frequencies (Popper and Fay 1993). A study done by Buscaino et al. (2009) found that nets equipped with high frequency pingers contained 28% more fish and were 31% less damaged compared to nets without pingers that experienced damage and predation by dolphins. A captive study done by Kastelein et al. (2007) found that higher frequency pingers were less likely to affect the behavior of marine fish (although a few species such as horse mackerel [*Trachurus trachurus*] and Atlantic herring [*Clupea harengus*] both exhibited reaction thresholds $\geq$ 2 kHz (0.1–2 kHz and 4 kHz respectively, Kastelein et al. [2008]) while low frequency (0.5–5kHz) sweep type pingers did elicit responses. Supporting that, a captive study by Goetz et al. (2015) which examined blood plasma cortisol concentration to quantify the stress level of European sardine (*Sardina pilchardus)* exposed to high frequency dolphin pingers, found minimal effect. Thus, researchers (Mann et al. 2001, Au and Hastings 2008) summarize that fish "generalists" typically experience drastic declines in sensitivity >0.5 kHz and "specialists" experience sensitivity up to 2.0 kHz and members of the clupeid group may be able to detect even higher frequency sound.

Management decisions regarding pinger development and deployment should take into consideration a lower frequency limit and the possible effects on fish catch rates. The challenge we are left with is to find a pinger that emits lower frequency tones that are within the range of seabird underwater sensitivity, but still outside the range of target fish hearing so that catch rates are not negatively affected. For the surf scoter, with the lowest frequency of sensitivity at 1.0 kHz, this may be impossible. However, since the surf scoter exists only in North America, management decisions can be made on a fisheries-specific level, taking into consideration whether the target fish species is a hearing generalist, in which case would be unaffected by a lower frequency pinger. The long-tailed ducks and common eider exhibited more discrepancy from fish sensitivity with peak sensitivity around 3.0 kHz. This discrepancy makes management solutions regarding pingers more straightforward, as a pinger that emits a tone in this range has the potential to be used in fisheries with fish species that were either generalists or specialists without affecting catch rates. Future Ocean's "Net Guard" whale pinger emits 3 kHz tones at 135 dB, and is an example of a commercially available pinger that has the potential to effectively deter species of seabird with underwater hearing sensitivities similar to that of long-tailed ducks and common eiders. The average audiogram for the three tested sea duck species showed thresholds of 101.6–114.2 dB re 1 μPa at 2.96 kHz. While a 135 dB tone is well above all three species' thresholds and would likely be heard at the source of the stimuli, this pinger may not be effective further from the source for the less acoustically sensitive species, the surf scoter. Further research should explore how grave of a threat bycatch in gillnets is for surf scoters in order to prioritize management decisions. As diving foragers, surf scoters have the characteristics that may make them vulnerable to gillnet bycatch (Regular et al. 2013). However, the literature does not present many instances of high bycatch-related mortalities for this species (Forsell 1999), and thus the need for acoustic deterrence might not be as great for surf scoters as it is for the more vulnerable species, like long-tailed ducks and eiders.

An alternative to using a pinger that is already commercially available is to develop a new acoustic deterrent device intended specifically for seabird deterrence. A pinger that emits a 2 kHz tone has the potential to be a "catch-all" for the three species tested in this study. The average long-tailed duck and common eider threshold values at 2 kHz were 105.8 and 106.4 dB re 1 μPa, respectively, and the average surf scoter threshold value was 109.6 dB re 1 μPa. While the surf scoter threshold is higher than the other species, this species is more likely to detect a signal at 2 kHz than 3 kHz. However, a 2 kHz pinger may emit tones within the range of fish hearing. Additionally, the scope of this study was limited to determining the baseline underwater hearing abilities of these species, and did not investigate whether an acoustic deterrent device would be effective in the goal of deterrence. Therefore, future research should first examine laboratory behavioral responses of these sea duck species to different pingers. Second, researchers should field-test successful lab-tested pingers in commercial gillnet fisheries (using established protocols, Dawson et al. 2013), with special consideration of unintended consequences such as drawing predators to the nets (i.e. "dinner bell effect", Bordino et al. 2002) or habituation by sea ducks to the pinger device over time (Amano et al. 2017). Last, I recommend that researchers investigate adding visual deterrents in the above tests. Vision may be directly involved in prey detection for many seabird species, thus making visual deterrents an appropriate method for reducing bycatch. A recent study examining the effectiveness of green LEDs in reducing gillnet bycatch of guanay cormorants (*Phalacrocorax bougainvillii)* found 85% reduction in bycatch for the nets containing the LEDs (Mangel et al. 2018). Additionally, Melvin et al. (1999) found decreased entanglement of murres and auklets when gillnets with high-visibility mesh was used and Trippel et al. (2003) found that nets using barium sulfate reduced bycatch of porpoises and seabirds. However, species from the family Anseriformes may rely on tactile cues from their bill for prey detection, putting less emphasis on visual cues. Even visually focused foragers must rely on other senses for detection, especially at deep depths or turbid waters (Martin & Crawford. 2015). Ultimately, a combination of methods may be the best option for deterring sea ducks.

REFERENCES

Amano, M., M. Kusumoto, M. Abe, and T. Akamatsu. 2017. Long-term effectiveness of pingers on a small population of finless porpoises in Japan. Endangered Species Research 32:35–40.

Anderson, O., C. Small, J. Croxall, E. Dunn, B. Sullivan, O. Yates, and A. Black. 2011. Global seabird bycatch in longline fisheries. Endangered Species Research 14:91–106.

Au, W. W. L., and M. C. Hastings. 2008. Principles of Marine Bioacoustics. Springer US, New York, NY.

Barlett, M. L., and G. R. Wilson. 2002. Characteristics of small boat acoustic signatures. The Journal of the Acoustical Society of America 112:2221.

Barlow, J., and G. A. Cameron. 2003. Field experiments show that acoustic pingers reduce marine mammal bycatch in the California drift gill net fishery. Marine Mammal Science 19:265–283.

Beason, R. C. 2004. What can birds hear? U.S. Department of Agriculture Wildlife Services, University of Nebraska, Lincoln, USA.

Bellebaum, J., B. Schirmeister, N. Sonntag, and S. Garthe. 2013. Decreasing but still high: bycatch of seabirds in gillnet fisheries along the German Baltic coast. Aquatic Conservation: Marine and Freshwater Ecosystems 23:210–221.

Benaka, L., L. F. Cimo, and L. Jenkins. 2012. Bycatch provisions in the reauthorized Magnuson-Stevens Act. Marine Fisheries Review 74:1–12.

Biju Kumar, A., and G. R. Deepthi. 2006. Trawling and by-catch: Implications on marine ecosystem. Current Science 90:922–931.

Bordino, P., S. Kraus, D. Albareda, A. Fazio, A. Palmerio, M. Mendez, and S. Botta. 2002. Reducing incidental mortality of Franciscana dolphin *Pontoporia blainvillei* with acoustic warning devices attached to fishing nets. Marine Mammal Science 18:833–842.

Borg, E. 1982. Auditory thresholds in rats of different age and strain. A behavioral and electrophysiological study. Hearing Research 8:101–115.

Burke, E. 2005. The effect of acoustic deterrent devices on bottlenose dolphin depredation in the Spanish mackerel gillnet fishery. Dissertation, Duke University, Durham, USA.

Buscaino, G., G. Buffa, G. Sarà, A. Bellante, A. J. Tonello, F. A. S. Hardt, M. J. Cremer, A. Bonanno, A. Cuttitta, and S. Mazzola. 2009. Pinger affects fish catch efficiency and damage to bottom gill nets related to bottlenose dolphins. Fisheries Science 75:537–544.

Caras, M. L., E. Brenowitz, and E. W. Rubel. 2010. Peripheral auditory processing changes seasonally in Gambel's white-crowned sparrow. Journal of Comparative Physiology A 196:581–599.

Castellote, M., C. W. Clark, and M. O. Lammers. 2012. Acoustic and behavioural changes by fin whales (*Balaenoptera physalus*) in response to shipping and airgun noise. Biological Conservation 147:115–122.

Cox, T. M., T. J. Ragen, A. J. Read, E. Vos, R. W. Baird, K. Balcomb, J. Barlow, J. Caldwell, T. Cranford, L. Crum, A. D'Amico, G. D. Spain, A. Fernandez, J. J. Finneran, R. Gentry, W. Gerth, F. Gulland, J. Hildebrand, D. Houser, T. Hullar, P. D. Jepson, D. Ketten, C. D. MacLeod, P. Miller, S. Moore, D. C. Mountain, D. Palka, P. Ponganis, S. Rommel, T. Rowles, B. Taylor, P. Tyack, D. Wartzok, R. Gisiner, J. Mead, and L. Benner. 2006. Understanding the impacts of antropogenic sound on beaked whales. Journal of Cetacean Research and Management 7:177–187.

Crowell, S. E., A. M. Wells-Berlin, C. E. Carr, G. H. Olsen, R. E. Therrien, S. E. Yannuzzi, and D. R. Ketten. 2015. A comparison of auditory brainstem responses across diving bird species. Journal of Comparative Physiology A 201:803–815.

Crowell, S. E., A. M. Wells-Berlin, R. E. Therrien, S. E. Yannuzzi, and C. E. Carr. 2016. In-air hearing of a diving duck: A comparison of psychoacoustic and auditory brainstem response thresholds. The Journal of the Acoustical Society of America 139:3001–3008.

Croxall, J. P., S. H. M. Butchart, B. Lascelles, A. J. Stattersfield, B. Sullivan, A. Symes, and P. Taylor. 2012. Seabird conservation status, threats and priority actions: A global assessment. Bird Conservation International 22:1–34.

Croxall, J. P., R. W. Davis, and M. J. O'Connell. 1988. Diving patterns in relation to diet of gentoo and macaroni penguins at south Georgia. The Condor 90:157–167.

Culik, B., S. Koschinski, N. Tregenza, and G. Ellis. 2001. Reactions of harbor porpoises *Phocoena phocoena* and herring *Clupea harengus* to acoustic alarms. Marine Ecology Progress Series 211:255–260.

D'Amico, A., R. C. Gisiner, D. R. Ketten, J. A. Hammock, C. Johnson, P. L. Tyack, and J. Mead. 2009. Beaked whale strandings and naval exercises. Aquatic Mammals 35:452–472.

Davies, R. W. D., S. J. Cripps, A. Nickson, and G. Porter. 2009. Defining and estimating global marine fisheries bycatch. Marine Policy 33:661–672.

Dawson, S., S. Northridge, D. Waples, and A. Read. 2013. To ping or not to ping: the use of active acoustic devices in mitigating interactions between small cetaceans and gillnet fisheries. Endangered Species Research 19:201–221.

Dayton, P. K., S. F. Thrush, M. Tundi Agardy, and R. J. Hofman. 1995. Environmental effects of marine fishing. Aquatic conservation marine and freshwater ecosystems 5:205–232.

Degel, A. H., I. K. Petersen, T. E. Holm, and J. Kahlert. 2010. Fugle som bifangst i garnfiskeriet Estimat af utilsigtet bifangst af havfugle i garnfiskeriet i området omkring Ærø. DTU Aqua-rapport 227–2010, Charlottenlund, Denmark.

DeMaster, D. P., C. W. Fowler, S. L. Perry, and M. F. Richlen. 2001. Predation and competition: the impact of fisheries on marine-mammal populations over the next one hundred years. Journal of Mammalogy 82:641–651.

Di Iorio, L., and C. W. Clark. 2010. Exposure to seismic survey alters blue whale acoustic communication. Biology Letters 6:51–54.

Dooling, R. J., J. A. Mulligan, and J. D. Miller. 1971. Auditory sensitivity and song spectrum of the common canary (*Serinus canarius*). The Journal of the Acoustical Society of America 50:700–709.

Dooling, R. J., and K. Okanoya. 1995. The method of constant stimuli in testing auditory sensitivity in small birds. Pages 161–169 *in* G. M. Klump, R. J. Dooling, R. R. Fay, and W. C. Stebbins, eds. Methods in Comparative Psychoacoustics. Birkhäuser Verlag, Switzerland.

Dooling, R. J., and J. C. Saunders. 1975. Hearing in the parakeet (*Melopsittacus undulatus*): Absolute thresholds, critical ratios, frequency difference limens, and vocalizations. Journal of Comparative and Physiological Psychology 88:1–20.

Ehrenstein, W. H., and A. Ehrenstein. 1999. Psychophysical methods. Pages 1211–1241 *in* U. Windhorst, and H. Johansson, eds. Modern Techniques in Neuroscience Research. Springer Berlin Heidelberg, Berlin, Germany.

Ellis, J. I., S. I. Wilhelm, A. Hedd, G. S. Fraser, G. J. Robertson, J.-F. Rail, M. Fowler, and K. H. Morgan. 2013. Mortality of migratory birds from marine commercial fisheries and offshore oil and gas production in Canada. Avian Conservation and Ecology 8:4.

Fay, R. R. 1988. Hearing in vertebrates: a psychophysics databook. Hill-Fay Associates, Winnetka, Illinois, USA.

Finneran, J. J., and D. S. Houser. 2006. Comparison of in-air evoked potential and underwater behavioral hearing thresholds in four bottlenose dolphins (*Tursiops truncatus*). The Journal of the Acoustical Society of America 119:3181–3192.

Forsell, D. J. 1999. Mortality of migratory waterbirds in Mid-Atlantic coastal anchored gillnets during March and April 1998. U.S. Fish and Wildlife Service, Chesapeake Bay Field Office, Annapolis, USA.

Gerstein, E. R., L. Gerstein, S. E. Forsythe, and J. E. Blue. 1999. The underwater audiogram of the West Indian manatee (*Trichechus manatus*). The Journal of the Acoustical Society of America 105:3575–3583.

Goetz, S., M. B. Santos, J. Vingada, D. C. Costas, A. G. Villanueva, and G. J. Pierce. 2015. Do pingers cause stress in fish? An experimental tank study with European sardine, *Sardina pilchardus* (Walbaum, 1792) (Actinopterygii, Clupeidae), exposed to a 70 kHz dolphin pinger. Hydrobiologia 749:83–96.

Gönener, S., and S. Bilgin. 2009. The effect of pingers on harbour porpoise, *Phocoena phocoena* bycatch and fishing effort in the turbot gill net fishery in the Turkish Black Sea coast. Turkish Journal of Fisheries and Aquatic Sciences 9:151–157.

Gordon, J., D. Gillespie, J. Potter, A. Frantzis, M. P. Simmonds, R. Swift, and D. Thompson. 2003. A review of the effects of seismic surveys on marine mammals. Marine Technology Society Journal 37:16–34.

Green, D. M. 1960. Auditory detection of a noise signal. The Journal of the Acoustical Society of America 32:121–131.

Green, D. M., and J. A. Swets. 1966. Signal detection theory and psychophysics. Wiley, New York, New York, USA.

Hall, J. W. 2007. New handbook of auditory evoked responses. Pearson, Boston, USA.

Hansen, K. A., A. Maxwell, U. Siebert, O. N. Larsen, and M. Wahlberg. 2017. Great cormorants (*Phalacrocorax carbo*) can detect auditory cues while diving. The Science of Nature 104:45.

Hawkins, A. D., and A. N. Popper. 2016. A sound approach to assessing the impact of underwater noise on marine fishes and invertebrates. ICES Journal of Marine Science 74:635–652.

Hildebrand, J. 2004. Sources of anthropogenic sound in the marine environment. Report to the Policy on Sound and Marine Mammals: An International Workshop. US Marine Mammal Commission and Joint Nature Conservation Committee, UK. London, England.

Hill, E. M. 2017. Audiogram of the mallard duck (*Anas platyrhynchos*) from 16 Hz to 9 kHz. Journal of Comparative Physiology A 203:929–934.

Hunt, G., and R. Furness, editors. 1996. Seabird/fish interactions, with particular reference to seabirds in the North Sea. International Council for the Exploration of the Sea Cooperative Research Report 216:1–87.

IBM Corporation. 2018. IBM SPSS Statistics for Windows, Version 26.0. Armonk, NY.Jepson, P. D., M. Arbelo, R. Deaville, I. A. P. Patterson, P. Castro, J. R. Baker, E. Degollada, H. M. Ross, P. Herráez, A. M. Pocknell, F. Rodríguez, F. E. Howie, A. Espinosa, R. J. Reid, J. R. Jaber, V. Martin, A. A. Cunningham, and A. Fernández. 2003. Gas-bubble lesions in stranded cetaceans. Nature 425:575–576.

Kastelein, R. A., M. Hagedoorn, W. W. L. Au, and D. de Haan. 2003. Audiogram of a striped dolphin (*Stenella coeruleoalba*). The Journal of the Acoustical Society of America 113:1130–1137.

Kastelein, R. A., S. van der Heul, J. van der Veen, W. C. Verboom, N. Jennings, D. de Haan, and P. J. H. Reijnders. 2007. Effects of acoustic alarms, designed to reduce small cetacean bycatch in gillnet fisheries, on the behaviour of North Sea fish species in a large tank. Marine Environmental Research 64:160–180.

Kastelein, R. A., S. van der Heul, W. C. Verboom, N. Jennings, J. van der Veen, and D. de Haan. 2008. Startle response of captive North Sea fish species to underwater tones between 0.1 and 64 kHz. Marine Environmental Research 65:369–377.

Kastelein, R. A., R. van Schie, W. C. Verboom, and D. de Haan. 2005. Underwater hearing sensitivity of a male and a female Steller sea lion (*Eumetopias jubatus*). The Journal of the Acoustical Society of America 118:1820–1829.

Köppl, C. 2015. Avian hearing. Pages 71–87 *in* C. G. Scanes, ed. Sturkie's Avian Physiology. Academic Press. New York, New York, USA.

Kraus, S. O. 1999. The once and future ping: Challenges for the use of acoustic deterrents in fisheries. Marine Technology Society Journal 33:90–93.

Kushlan, J. A., M. J. Steinkamp, K. C. Parsons, J. Capp, M. A. Cruz, M. Coulter, I. Davidson, L. Dickson, N. Edleson, R. Elliot, R. M. Erwin, S. Hatch, S. Kress, R. Milko, S. Miller, K. Mills, R. Pail, R. Phillips, J. E. Saliva, B. Sydeman, J. Trapp, J. Wheeler, and K. Wohl. 2002. Waterbird conservation for the Americas: The North American waterbird conservation plan, version 1. Waterbird Conservation for the Americas, Washington D.C., USA.

Larsen, F., and C. Krog. 2007. Fishery trials with increased pinger spacing. Paper SC/59/SM2. IWC Scientific Committee Meeting, Anchorage, Alaska, USA.

Lewison, R. L., L. B. Crowder, A. J. Read, and S. A. Freeman. 2004. Understanding impacts of fisheries bycatch on marine megafauna. Trends in Ecology and Evolution 19:598–604.

Lewison, R. L., L. B. Crowder, B. P. Wallace, J. E. Moore, T. Cox, R. Zydelis, S. McDonald, A. DiMatteo, D. C. Dunn, C. Y. Kot, R. Bjorkland, S. Kelez, C. Soykan, K. R. Stewart, M. Sims, A. Boustany, A. J. Read, P. Halpin, W. J. Nichols, and C. Safina. 2014. Global patterns of marine mammal, seabird, and sea turtle bycatch reveal taxa-specific and cumulative megafauna hotspots. Proceedings of the National Academy of Sciences 111:5271–5276.

Lillis, A., D. B. Eggleston, and D. W. R. Bohnenstiehl. 2016. Soundscapes and larval settlement: Characterizing the stimulus from a larval perspective. Pages 637–645 *in* A. N. Popper and A. Hawkins, eds. The effects of noise on aquatic life II, Advances in experimental medicine and biology. Springer, New York, USA.

Maiorana, V. A., and W. M. Schleidt. 1972. The auditory sensitivity of the turkey. Journal of Auditory Research 12:203–207.

Mangel, J. C., J. Wang, J. Alfaro-Shigueto, S. Pingo, A. Jimenez, F. Carvalho, Y. Swimmer, and B. J. Godley. 2018. Illuminating gillnets to save seabirds and the potential for multi-taxa bycatch mitigation. Royal Society Open Science 5:180254.

Manville, A. M. 2005. Seabird and waterbird bycatch in fishing gear : Next steps in dealing with a problem. Pages 1071-1082 *in* J. C. Ralph and D. Terrell, eds. Bird Conservation Implementation and Integration in the Americas: Proceedings of the Third International Partners in Flight Conference. U.S. Forest Service General Technical Report PSW-GTR-191, Albany, New York, USA.

Markov, V. 1977. Underwater sounds in macaroni penguins. Pages 111–121 *in* Adaptations of Penguins. Moscow, Russia.

Maxwell, A., K. A. Hansen, S. T. Ortiz, O. N. Larsen, U. Siebert, and M. Wahlberg. 2017. In-air hearing of the great cormorant (*Phalacrocorax carbo*). Biology Open 6:496–502.

Melvin, E. F., J. K. Parrish, and L. L. Conquest. 1999. Novel tools to reduce seabird bycatch in coastal gillnet fisheries. Conservation Biology 13:1386–1397.

Merkel, F. 2011. Gillnet bycatch of seabirds in South-west Greenland, 2003–2008. Greenland Institute of Natural Resources Technical Report, 85, Nuuk, Greenland.

Mitchell, E. 1975. Review of biology and fisheries for smaller cetaceans. Journal of the Fisheries Research Board of Canada 32:875–877.

Moore, J. E., B. P. Wallace, R. L. Lewison, R. Žydelis, T. M. Cox, and L. B. Crowder. 2009. A review of marine mammal, sea turtle and seabird bycatch in USA fisheries and the role of policy in shaping management. Marine Policy 33:435–451.

National Marine Fisheries Service. 1978. The Marine Mammal Protection Act of 1972. Annual Report. Silver Spring, Maryland, USA.

National Oceanic and Atrmospheric Administration. 2009. Fisheries of the exclusive economic zone off Alaska. United States Federal Register 74:27498–27504.

National Oceanic and Atmospheric Administration. 2010. Taking of marine mammals incidental to commercial fishing operations; harbor porpoise take reduction plan regulations. United States Federal Register 75:7383–7402.

National Research Council. 1990. Decline of the sea turtles: causes and prevention. National Academy Press, Washington, D.C., USA.

Perry, M. C., A. M. Wells-Berlin, D. M. Kidwell, and P. C. Osenton. 2009. Temporal changes of populations and trophic relationships of wintering diving ducks in Chesapeake Bay. Waterbirds 30:4–16.

Pichegru, L., R. Nyengera, A. M. McInnes, and P. Pistorius. 2017. Avoidance of seismic survey activities by penguins. Scientific Reports 7:16305.

Popper, A. N., and R. R. Fay. 1993. Sound detection and processing by fish: Critical review and major research questions. Brain, Behavior and Evolution 41:14–25.

Popper, A. N., A.D. Hawkins, R.R. Fay, D.A. Mann, S. Bartol, T.J. Carlson, S. Coombs, W.T. Ellison, R.L. Gentry, M.B. Halvorsen, S. Løkkeborg, P.H. Rogers, B.L. Southall, D.G. Zeddies, and W.N. Tavolga. 2014. ASA S3/SC1.4 TR-2014 Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report Prepared by ANSI-Accredited Standards Committee S3/SC1 and Registered with ANSI. Springer, New York, USA.

Pott, C., and D. A. Wiedenfeld. 2017. Information gaps limit our understanding of seabird bycatch in global fisheries. Biological Conservation 210:192–204.

Prior, N. H., E. Smith, S. Lawson, G. F. Ball, and R. J. Dooling. 2018. Acoustic fine structure may encode biologically relevant information for zebra finches. Scientific Reports 8:6212.

Read, A. J., P. Drinker, and S. Northridge. 2006. Bycatch of marine mammals in U.S. and global fisheries. Conservation Biology 20:163–169.

Reeves, R., K. McClellan, and T. Werner. 2013. Marine mammal bycatch in gillnet and other entangling net fisheries, 1990 to 2011. Endangered Species Research 20:71–97.

Regular, P., W. Montevecchi, A. Hedd, G. Robertson, and S. Wilhelm. 2013. Canadian fishery closures provide a large-scale test of the impact of gillnet bycatch on seabird populations. Biology Letters 9:20130088–20130088.

Richardson, W. J. 1995. Marine mammals and noise. Academic Press, San Diego, California, USA.

Robertson, G., and R. Gales, editors. 1998. Albatross biology and conservation. Surrey Beatty and Sons, Chipping Norton, Australia.

Sadé, J., Y. Handrich, J. Bernheim, and D. Cohen. 2008. Pressure equilibration in the penguin middle ear. Acta Oto-Laryngologica 128:18–21.

Saunders, J.C., R. K. Duncan, D. E. Doan, and Y. L. Werner. 2002. The middle ear of reptiles and birds. Pages 13–69 *in* R. J. Dooling, R. R. Fay, and A. H. Popper, eds. Comparative Hearing: Birds and Reptiles. Springer-Verlag. New York, New York, USA.

Simpson, W. A. 1988. The method of constant stimuli is efficient. Perception and Psychophysics 44:433–436.

Skinner, B. F. 2015. Cumulative record: Definitive edition. B. F. Skinner Foundation, Cambridge, Massachussetts, USA.

Southall, B. L., A. E. Bowles, W. T. Ellison, J. J. Finneran, R. L. Gentry, C. R. Greene, D. Kastak, D. R. Ketten, J. H. Miller, P. E. Nachtigall, W. J. Richardson, J. A. Thomas, and P. L. Tyack. 2009. Marine mammal noise exposure criteria: Initial scientific recommendations. The Journal of the Acoustical Society of America 125:2517–2517.

Szymanski, M. D., D. E. Bain, K. Kiehl, S. Pennington, S. Wong, and K. R. Henry. 1999. Killer whale (*Orcinus orca*) hearing: Auditory brainstem response and behavioral audiograms. The Journal of the Acoustical Society of America 106:1134–1141.

Therrien, S. 2014. In-air and underwater hearing of diving birds. Dissertation, University of Maryland, College Park, USA.

Trainer, J. 1946. Auditory acuity of certain birds. Cornell University, Ithaca, New York, USA.

Trippel, E. A., N. L. Holy, D. L. Palka, T. D. Shepherd, G. D. Melvin, and J. M. Terhune. 2003. Nylon barium sulphate gillnet reduces porpoise and seabird mortality. Marine Mammal Science 19:240–243.

Trippel, E. A., M. B. Strong, J. M. Terhune, and J. D. Conway. 1999. Mitigation of harbour porpoise (*Phocoena phocoena*) by-catch in the gillnet fishery in the lower Bay of Fundy. Canadian Journal of Fisheries and Aquatic Sciences 56:113–123.

Wartzok, D., and D. Ketten. 1999. Marine Mammal Sensory Systems. Pages 117–175 *in* J. Reynolds and S. Rommel, eds. Biology of Marine Mammals. Smithsonian Institution Press. Washington D.C., USA.

Washington Department of Fish and Wildlife. 2017. Puget sound commercial salmon regulation. Olympia, USA. <http://wdfw.wa.gov/publications/01743/wdfw01743.pdf> Last accessed 3/19/2019.

Wever, E. G., P. N. Herman, J. A. Simmons, and D. R. Hertzler. 1969. Hearing in the blackfooted penguin, *Spheniscus demersus*, as represented by the cochlear. Proceedings of the National Academy of Sciences 63: 676–680.

Whitehead, H., J. Christal, and S. Dufault. 1997. Past and distant whaling and the rapid decline of sperm whales off the Galapagos Islands. Conservation Biology 11:1387–1396.

Wolski, L. F., R. C. Anderson, A. E. Bowles, and P. K. Yochem. 2003. Measuring hearing in the harbor seal (*Phoca vitulina*): Comparison of behavioral and auditory brainstem response techniques. The Journal of the Acoustical Society of America 113:629–637.

Žydelis, R., J. Bellebaum, H. Österblom, M. Vetemaa, B. Schirmeister, A. Stipniece, M. Dagys, M. van Eerden, and S. Garthe. 2009. Bycatch in gillnet fisheries: An overlooked threat to waterbird populations. Biological Conservation 142:1269–1281.

Žydelis, R., C. Small, and G. French. 2013. The incidental catch of seabirds in gillnet fisheries: A global review. Biological Conservation 162:76–88.

Appendix A

IACUC APPROVAL

USGS Patuxent Wildlife Research Center
12100 Beech Forest Road
Laurel, Maryland 20708-4039

SOP No. 007, Form 2
Date: September 2013
Replaces: May 2006
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ACUC Form 2: Significant Changes Form

Instructions: The Significant Changes Form is for significant modifications to a study that require ACUC review. Please retitle the electronic version of this document using ACUC ID#, PI last name, "Form 2", and today's date (e.g. 2013-1_Smith_Form 2_10-03-13.DOC). *Please use the ACUC ID# assigned to your original study*. Complete the following form by typing your responses into the provided answer boxes; they will expand to accommodate your answers. Please update the date in document title if revised versions are required by the committee.

ACUC ID# and Original Study Plan Title:	ID# 2012-06: Auditory Brainstem Response of Seaducks and Diving Ducks	Original ACUC Approval Date: 7/3/2012
Revised Title (if applicable):	Underwater Hearing Thresholds and Assessment of Auditory Deterrents on Diving Birds	Today's Date: 03/16/16
Principal Investigator(s):	Alicia Berlin and Glenn Olsen	
Branch Chief (Supervisor):	Linda Weir	

1. **Briefly describe original study and associated procedures.**

This is an investigation of the in-air and underwater hearing abilities of seabirds, including both electrophysiological and behavioral methods. To test hearing, we have used the auditory brainstem response, which is a neural response to acoustic stimuli, recorded by subdermal electrodes while a bird is under anesthesia. We have also used behavioral methods (psychoacoustics), in which birds are trained to behaviorally respond to acoustic stimuli with a particular behavior (pecking a target).

2. **Please specify and justify the changes being proposed.**

We are continuing and expanding the project. We are continuing the auditory brainstem response experiments, and expanding them from solely in-air to underwater testing. We are continuing the behavioral hearing tests with the same methods as before, to expand our underwater data. We are also adding a project to investigate the effectiveness of acoustic deterrent devices on seabirds. These continuations and expansions are to meet our partners and USGS science needs. This project will continue for the next three years.

3. **Have there been any unanticipated mortalities or significant injuries in original study? If so, how many, what happened and who performed the necropsies?**

No.

4. **Please answer the following questions:**

Will the number, species or marking method change under the modified study plan?	___Yes (explain above in #2) __X_No

USGS Patuxent Wildlife Research Center
12100 Beech Forest Road
Laurel, Maryland 20708-4039

SOP No. 007, Form 2
Date: September 2013
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Will housing or general care of animals change?	___Yes (explain above in #2) _X_ No
Will timeframe of original project change?	_X_Yes. (explain above in #2) ___No
Will substances to be administered or procedures to be performed change?	___Yes (explain above in #2) _X_No
Will euthanasia procedures or disposition of animals change?	_X_ No ___Yes (explain above in #2) If yes, is new procedure AVMA approved? ____Yes ____No

I certify that the above responses are a true and accurate reporting of the animal activities proposed/conducted. I certify that this project plan follows the Animal Welfare Act and applicable guidelines for the care and use of animals.

Alicia M. Berlin

Signature of Principal Investigator

3/17/16
Date

Signature of Branch Chief (USGS) or Supervisor

3/22/16
Date