2014

Using a Sonic Net to Deter Pest Bird Species: Excluding European Starlings from Food Sources by Disrupting their Acoustic Environment

Ghazi Mahjoub
College of William & Mary - Arts & Sciences

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Food Sources by Disrupting their Acoustic Environment

Ghazi Mahjoub

Annandale, Virginia

Bachelors of Science in Biology, Virginia Polytechnic Institute and State
University, 2012

A thesis presented to the Graduate Faculty
of the College of William and Mary in Candidacy for the Degree of
Master of Science
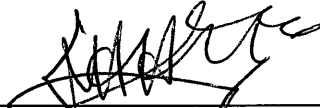
Department of Biology

The College of William and Mary
May 2014

APPROVAL PAGE
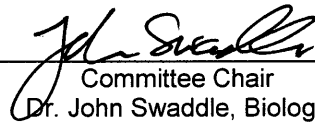
This thesis is submitted in partial fulfillment of
the requirements for the degree of

Master of Science
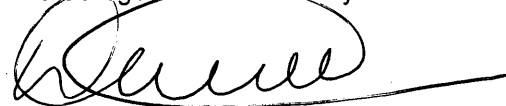
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Ghazi Mahjoub

Approved by the Committee, April, 2014
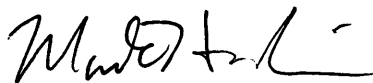
_____
Committee Chair
Dr. John Swaddle, Biology
The College of William & Mary

_____
Dr. Daniel Cristol, Biology
The College of William & Mary

_____
Dr. Matthias Leu, Biology
The College of William & Mary

_____
Dr. Mark Hinders, Applied Science
The College of William & Mary

COMPLIANCE PAGE

Research approved by

<u>Institutional Animal Care and Use Committee (IACUC)</u>

Protocol number(s): IACUC-2012-11-23-jpswad

Date(s) of approval: 2012-12-23

ABSTRACT

Pest avian wildlife is responsible for substantial economic damage every year in the United States. In this study we focused on altering the foraging behavior of the European starling (*Sturnus vulgaris*), a pest bird that is responsible for crop losses and also poses significant risk for bird-aircraft strikes. The goal of our project was to develop an effective system to limit starlings' access to a food patch. Previous technologies used to deter starlings have generally failed as birds quickly habituate to startle regimes. Using non-linear ultrasonic parametric arrays, we broadcast a directional sound that overlapped in frequency with starling vocalizations and was contained in a specific area creating a "net". We hypothesized that the "sonic net" would disturb acoustic communication for starlings, causing them to leave and feed elsewhere. Using wild-caught starlings in a large aviary, we deployed the sonic net over one food patch while leaving another food patch unaltered and then assessed their presence and feeding for three consecutive days. The sonic treatment decreased starlings' presence at the treated food patch, on average by 46%. Additionally, we assessed whether the sonic net disrupted the birds' response to an alarm call. When under the sonic net, starlings did not respond to the alarm call, suggesting that the sonic net disrupted acoustic communication. The sonic net is a promising new method of decreasing foraging activity by pest bird species, which has important implications for protecting crops, and deterring birds from airports and other sites of socio-economic importance.

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1- INTRODUCTION

Agriculture, manmade structures and the aviation industry suffer losses due to destruction and hazard caused by birds (Pimentel et al. 2000). For example, conservative estimates suggest that damages and delays following bird strikes cost the aviation industry and its insurers $1.2 billion per year (Allan 2006). Such economic impacts do not account for loss of life, which can also result from birds striking aircraft (Linz et al. 2007). The annual economic costs due to the overall damage caused by pest birds has been estimated at $1.9 billion in the US (Pimentel et al. 2005).

Numerous technologies have been developed to deter pest birds from socio-economically significant areas. Many of these systems use auditory stimuli such as species specific alarm calls, predator calls, loud noises and pyrotechnics (Bomford and O'Brien 1990). Other methods rely on visual cues to deter the birds (Bruggers et al. 1986, Dolbeer et al. 1986, Tobin et al. 1988, McLennan et al. 1995, Avery et al. 2002, Blackwell et al. 2002, Sodhi 2002, Sherman and Barras 2004). Chemical treatment of food sources, such as agricultural crops, can also deter or cause harm to birds (Sayre and Clark 2001). Here, we review each of these categories of avian deterrents, organized by sensory modality, and comment on their sustainable effectiveness for keeping birds away from socio-economically important areas.

a- Auditory repellents:

Auditory repellents produce sonic, ultrasonic or bio-sonic calls that help to keep birds away from a specific target area (DeVault et al. 2013). In general, birds respond to bio-sonic stimuli (i.e., recorded alarm calls, distress call) by fleeing the site, at least in theory (Lima and Dill 1990). Researchers have also assumed that birds are unlikely to habituate to these bio-sonic stimuli because of their biological relevance (Bomford and O'Brien 1990) and that anti-predatory response could be evolutionarily conserved (Lima and Dill 1990). Response to such alarm calls varies among species (DeVault et al. 2013) and by species ecology (Goodale and Kotagama 2008). Importantly, there is evidence of habituation to bio-sonic stimuli. For example , European starlings (*Sturnus vulgaris)* stopped responding to an alarm call after approximately seven days in the absence of negative reinforcement (Summers 1985). Bio-sonic stimuli are thus limited by context, species, species behavior, and ecology (DeVault et al. 2013).

Ultrasonic repellents have commonly been commercialized as effective bird repellents (Bomford and O'Brien 1990) that are non-audible to humans and thus can be used in places where humans are often present and where they will not be able to hear them. However these stimuli are rarely effective, in part because of the irrelevance of the stimulus for most birds, which do not hear in the ultrasonic range (>20 kHz) (DeVault et al. 2013). The use of loud noises such as those produced by propane exploders or pyrotechnics is very common (Bomford and O'Brien 1990). The repellency of these systems relies on the underlying fear

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induced by the loud stimulus (DeVault et al. 2013). These extreme startle stimuli show effectiveness at a small scale especially if installed before the birds establish a feeding habit in the target location (Cummings et al. 1986). The effectiveness of propane canons requires that they are constantly moved from one location to another to maintain novelty and avoid habituation (Linz et al. 2011). Such an approach is labor intensive and costly and relies on monitoring of bird activities. The loud noises are also bothersome to humans at a great distance.

b- Visual deterrent

Visual bird deterrents have been used in airport environments and agricultural fields. These types of deterrents are designed to invoke a fear response. Eye-spot balls have been used in vineyards where their initial effectiveness decreased prior to fruit ripening, by which time starlings returned to their initial numbers (McLennan et al. 1995). In some cases, reflecting tape is used as a visual bird deterrent. In a study where reflecting tape was applied to different crops in four different countries, researchers found that this method can be effective with certain species at a small scale while other species habituated to the reflecting tape treatment within a short period following the application (Bruggers et al. 1986). Another study found similar results, where the researchers determined that reflecting tape can be effective at deterring certain species of birds but installation and maintenance are not cost effective at a large

scale (Dolbeer et al. 1986). Additionally, reflective tape failed at deterring American robins (*Turdus migratorius*), starlings, and house finches (*Carpodacus mexicanus*) from blueberry fields (Tobin et al. 1988). These three studies demonstrated the ineffectiveness of reflecting tape at deterring birds from agricultural fields.

In certain airport environments, predators such as border collies (Sodhi 2002) and trained falcons (Kitowski et al.) are currently used to discourage the presence of birds. Although these methods can be effective a deterring certain bird species, they require intensive labor and can be costly. Handheld lasers have recently been employed (Blackwell et al. 2002) in airport environments. The effectiveness of lasers as bird deterrents is still debatable; some research has shown that certain bird species had limited response to the stimulus and the usefulness of lasers is highly dependent on ambient light conditions (Sherman and Barras 2004). Lasers also require airport personnel to constantly move to direct the beam at the birds that need to be dispersed thus making this method time consuming and inefficient.

c- *Chemical deterrents and avicides:*

Chemical compounds are also commonly used to deter birds from sensitive crops and airport environments (DeVault et al. 2013). Only two chemical repellents are currently registered for use in the USA: methyl anthranilate (MA) and anthraquinone (AQ). These two chemicals are classified

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as primary and secondary repellents respectively (DeVault et al. 2013). The mode of action of primary repellents differs from secondary repellents in that primary repellents do not require learning to be effective.

Methyl anthranilate is a primary repellent organic compound extracted from grapes (Esther et al. 2013) and is often used in human food as a flavoring ingredient. Chemicals under this category tend to provoke a reflexive withdrawal or escape behavior in birds. This is mainly because methyl anthranilate (hereafter MA) has an unpalatable taste, an unpleasant smell or an irritating effect on the eyes (Sayre and Clark 2001). Methyl anthranilate has been investigated since the early 1960s (Kare 1961). Early studies looked at MA repellency to European starlings, common grackles (*Quiscalus quiscula*), red-winged blackbirds (*Agelaius phoeniceus*), and brown-headed cowbirds (*Molothrus ater*) in livestock feed lots (Mason et al. 1985). Others studied the potential repellency of MA on blackbirds (*Icteridae sp.*) and cedar waxwings (*Bombycilla cedrorum*) in high values crops (i.e. sweet cherries, blueberries, and grapes) (Curtis et al. 1994, Cummings et al. 1995) and on blackbirds in sunflower fields (Werner et al. 2005). Although some studies showed potential repellency of MA at for certain bird species (Stevens and Clark 1998, Engeman et al. 2002) other studies showed that MA is ineffective at deterring birds either in captivity or in the field (Cummings et al. 1995, Werner et al. 2005).

Secondary repellents evoke an adverse physiological effect (e.g. gastrointestinal illness), which the animal associates with a sensory cue (e.g., taste, odor, visual cue) and then learns to avoid. Anthraquinone was identified as a potential bird repellent in the early 1940s (Heckmanns and Meisenheimer 1944). Many studies have since identified this chemical as an effective bird repellent. Early studies showed that anthraquinone effectively repels boat-tailed grackles and red-winged blackbirds from newly planted rice (Avery et al. 1998a, Avery et al. 2000). More recent studies have shown that anthraquinone-based repellents are effective at deterring Canada geese (*Branta canadensis*), red-winged blackbirds, and ring-necked pheasants (*Phasianus colchicus*) from corn seeds and ripening corn (Werner et al. 2009, Carlson et al. 2013). Other studies have shown successful repellency to red-winged blackbirds from drill-planted rice (Cummings et al. 2011), ring-necked pheasants, and common grackles from sunflower crops (Werner et al. 2011).

Although non-lethal chemical repellents are a socially acceptable approach to managing avian depredation of agricultural crops (Linz et al. 2006, Werner et al. 2011) chemical toxicants such as anthraquinone, which promote a learned response, are often derivatives of synthetic pesticides (Fagerstone and Schafer 1998). As a consequence, potent secondary repellents often have undesirable consequences, either directly in the form of physiological or metabolic side effects or side effects because of their degradation products

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(Dolbeer et al. 1994). Thus, there is a need to vigorously identify chemicals that are potent repellents but, safe for animal use, and the environment.

The use of primary repellents has been promoted as filling the need for effective, environmentally safe products (Mason and Clark 1992). Primary repellents are reflexively rejected because they are acutely irritating. As such, the target animal never exposes itself to sufficient dosages that would cause severe gastrointestinal illness (Sayre and Clark 2001). Despite these positive attributes, primary repellents have not achieved the success of secondary repellents in the field. Because primary repellents are frequently more benign in their biological effects on the target organisms (Sayre and Clark 2001) and also because they can easily biodegrade (Aronov and Clark 1996) or wash away with rain and irrigation (Werner et al. 2005) they rapidly lose potency and thus require repeated treatments depending on the season and crops treated. Therefore, this form of bird deterrence can be expensive to maintain and can result in chemical residues on crops and in runoff water (Aronov and Clark 1996). A comprehensive economic study of MA and AQ use in different environments is still missing from the current literature and would be highly useful in deciding whether these chemicals are economically viable alternatives.

Avicides such as DRC-1339 (3-chloro-4-methylaniline hydrochloride) can reduce pest bird populations through direct mortality (Homan et al. 2005, Homan et al. 2013) but can also affect non-target species (Avery et al. 1998b, Linder et

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al. 2004). The application of DRC-1339 is often not cost effective (Blackwell et al. 2003, Linz et al. 2012).

Making long-term physical habitat changes to exclude birds is not a preferred solution due to the high environmental costs (Blackwell et al. 2009a). Direct control, such as trapping and euthanizing large numbers of pest birds to protect agricultural and industrial structures, often has little to no impact on the overall pest population because these bird populations tend to be very large (Homan et al. 2005).Many avian repellents are untested, temporarily effective, or cost-prohibitive. These technologies undergo dramatically diminished success rates within a few days, or even hours, due to quick habituation (Bomford 1990, Bomford and O'Brien 1990, Belant et al. 1998) which makes these devices neither effective nor economically sustainable for a long-term application (LeMieux 2009).

Although many of the deterrence techniques reviewed above are not effective, a combination of them is often used in agricultural fields and in airport environments. However, there are currently no published reports on the effectiveness of using certain deterrent combination in agriculture and in airports.

The development of more effective methods to reduce the associated economic impacts will require an understanding of the evolutionary and ecological basis of bird feeding and predatory avoidance behavior. Specifically, we studied the European starling (*Sturnus vulgaris*) as a model pest bird and

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report experiments in which we manipulate the acoustic environment of these birds so as to mask acoustic communication and displace flocks of starlings from food sources. In agriculture European starlings have been estimated to cause $800 million of damage per year (Pimentel et al. 2005). Because these birds often roost and feed in large numbers near airports they also pose a substantial risk for aircraft (Linz et al. 2007). Therefore, there is societal interest in displacing flocks of European starlings. An integrated understanding of birds' sensory ecology and associated behaviors can aid the development of effective and sustainable methods of pest bird exclusion (Blackwell et al. 2009a, Blackwell et al. 2009b).

European starlings use vocal communication for mating calls, territorial defense, and to indicate the quality and location of food or to warn of approaching predators (Feare 1984). In other species, if environmental noises overlap with the frequency range (i.e. acoustic pitch) of bird communication the birds exposed to noise may suffer fitness deficits (Klump 1996, Brumm and Slabbekoorn 2005, Barber et al. 2010, Kight and Swaddle 2011, Kight et al. 2012), likely because vocalizations are acoustically masked by noise and birds cannot hear each other effectively (Klump 1996, Wiley 2006). Importantly, we also know that environmental noise that overlaps with avian communication can displace some bird populations and restructure ecological communities (Francis et al. 2011). Here we build on these observations and employ a noise that is designed to overlap with European starling vocal communication and investigate

whether a spatially controlled introduction of this noise, which we term a "sonic net", effectively displaces starlings from a food source and also prevents starlings from responding to an alarm call playback.

To create our "sonic nets", we employed ultrasonic parametric arrays to produce a highly directional beam of sound in the 2-10 kHz range at an amplitude of approximately 80dB SPL (sound pressure level) at the food sources (Dieckman et al. 2013). Conventional loud speakers emit sound in a non-directional way (Gan et al. 2012). However ultrasonic parametric arrays transmit a highly directional sound beam much like a spotlight (Yoneyama et al. 1983, Pompei 1999, Gan et al. 2012). The beam starts out as a mixture of two ultrasonic frequencies. A non-linear conversion interaction between the sound waves results in an audible sound that is the difference between the two ultrasound frequencies and which remains highly directional. By applying our sonic net to one food source and not the other in a large aviary over three consecutive days we examined whether this type of controlled sound can displace flocks and lessen the amount of food eaten. We hypothesized that starlings would be deterred from feeding at the food patch affected by the sonic net. We also investigated whether our sonic net reduced starlings' response to an alarm call playback. We hypothesized that the 2-10 kHz sound would mask perception of the alarm call, leading to a relative lack of increase in vigilance behaviors when the alarm call was played.

2- METHODS

a- Subjects and general housing

Seventy wild-caught adult European starlings, trapped during February 2013 in Columbus KS. Ten flocks of seven birds were housed in large outdoor cages (3 m × 2.5 m × 2 m) with ad libitum access to nutritionally-complete food (Bartlett Milling, Statesville, NC), drinking water, and perches. The housing cages were visually and acoustically isolated from the experimental aviary. We identified the sex of all birds and applied numbered and colored leg bands for easy identification.

b- Aviary experiment

Each experimental trial was performed on one flock of six birds at a time (out of the seven in a cage, leaving one extra bird in case of injury) from May-July, 2013. Prior to an experimental trial the birds were food deprived for two hours to encourage foraging behavior (Devereux et al. 2006, Quinn et al. 2006). Experiments took place when there was no rain and less than 16 km/h winds as the interaction of rain and wind with the aviary roof created loud artificial noise that would hinder experiments.

Each flock was acclimated to the experimental aviary (Fig. 1) 24 hours prior to the beginning of a noise treatment sequence (Fig. 2). Each treatment day started at 0900 and ended at 1700. The experimental aviary was a long U-shaped cage where the birds could access a food patch at both ends, and where

the food patches were connected by a long area that contained only water. Hence, birds had to feed either at patch A or patch B (Fig. 1). In the eight hour trials birds had sufficient time to feed at both ends of the aviary and were always observed to feed at both ends on their acclimation day (i.e. before sonic net exposure). At the beginning of every day, including experimental trial days, we placed 500 g of food in a standardized tray at both patch A and B. The tray was large enough to catch food spilled by the birds.

On the day following the acclimation day we performed a baseline trial (day 1) where a flock of birds was not exposed to any additional noise (i.e. the sonic net) at either patch A or B. We recorded the birds' presence and foraging using a four camera closed circuit television (CCTV) system (Lorex Inc, Ontario, Canada). From these recordings we counted the number of birds at both patch A and B every five minutes of the eight hour trial and also recorded whether the birds were feeding. We also measured the mass (g) of food eaten from patches A and B. On the next day we commenced a series of three noise treatment days in which one of the food patches (A or B) was affected by the presence of a sonic net. This sonic net was produced by broadcasting a noise in the 2-10 kHz range at approximately 80 dB SPL using an MP3 player connected to an Audiospotlight parametric array speaker (Holosonics, Watertown, MA). High-amplitude broad-frequency noise may mask important signals that birds might be transmitting (Swaddle et al. 2006). The high directionality of the noise produced by the parametric array allowed us to fill side A or B with noise without any noise

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leakage to the opposite side, which was confirmed by sound recordings at untreated patches.

For half of the flocks (randomly determined) the sonic net was applied at patch A on day 2, patch B on day 3, and patch B again on day 4 (i.e. an ABB pattern) (Fig. 2). For the other flocks the sonic net was applied at patch B on day 2, patch A on day 3, and patch A again on day 4 (i.e. a BAA pattern) (Fig. 2). This sequencing allowed us to control for side-bias among the groups of starlings. A visually similar mock speaker was placed on the quiet side to control. For the baseline trial, we used the CCTV system to record the presence and foraging behaviors of the birds in each of the noise treatment trials and we also measured how much food was eaten at patches A and B.

Analysis 1: Aviary experiment.—We measured the number of birds present and the number of birds foraging at either patch by analyzing a frame of each video every 5 min of each 8 h trial. A bird was recorded as present if it was perched, on the ground, hanging on the side of the aviary, or foraging. The percentage of birds on either side was divided by total daily observations on both sides of the aviary to get a percentage of bird present or foraging on either side (Appendix). A bird was recorded as foraging if it was feeding or sitting in the provided food dish. The amount of food consumed in the eight hour trials was calculated by subtracting the weight of food remaining in the food dish at the end of the trial (after removal of feces) from the initial 500 g provided on each side.

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We tested whether the 2-10 kHz sonic net affected the presence of starlings, the feeding behavior of birds, and the amount of food eaten with repeated-measures ANOVAs with both the treated side of the aviary and day of the experiment as within-subjects independent variables. We also explored whether the effectiveness of the sonic net on birds' presence and feeding changed over the three days of the experiment by examining the interaction of the sonic net treatment with day of the experiment (treatment by day interaction).

c- Alarm call experiment

We also performed a captive experiment to test whether starling responses to a broadcast conspecific alarm call were lower in the presence of a sonic net. We conducted trials to assess birds' change in vigilance in response to an alarm call on eighteen groups of three randomly chosen starlings (no birds were tested more than once) from August-October, 2013. The groups of three birds were placed in a small cage (0.9 m × 0.75 m × 0.4 m) 24 h prior to the trials to acclimate to the experimental cage setting with *ad libitum* food and water. Birds were food deprived on experimental days for 1 h prior to the trials to encourage feeding behavior. In the experimental cage, the group was provided with two small water dishes and a small food dish with their standard food. We placed mealworms in a sand tray below the mesh cage bottom. The mealworms were able to burrow in the sand which motivated the birds to probe to locate them and thus feed frequently. The parametric array speaker was placed four meters away

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and the same 2-10 kHz noise used in the aviary experiment was broadcast at 80 dB SPL.

To start each experiment a group of birds was given five minutes to acclimate and then experienced a two treatment sequence (a quiet treatment followed by a sonic net or sonic net followed by a quiet treatment). Nine of the eighteen experimental flocks experienced a treatment sequence that started with a quiet control treatment followed by the sonic net treatment. The remaining nine flocks experienced a treatment sequence that began with the sonic net treatment and was followed by a quiet control treatment. This alternation in treatments allowed us to control for the effects that the order of the treatments could have had on the behavioral response of the birds. Each treatment lasted 10 min and at the end of the first 5 min of each treatment a 2 s alarm call was played three times in quick succession (Fig. 3). The broadcast starling alarm call spectrum was within the 3-9 kHz range (Feare 1984) and thus would be masked by the overlapping 2-10 kHz range sonic net. The alarm call was broadcast using non-directional speakers placed a meter from the experimental cage and was also broadcast at 80 dB SPL relative to the center of the birds' cage.

The 2-10 kHz sonic net could also have altered the birds' behavior simply because it was a loud sound rather than specifically masking the perception of the alarm call. We tested fourteen flocks under a white noise broadcast in the 0.1-2 kHz range at 80 dB SPL using the same treatment sequence. The lower

frequency range sound was not predicted to mask perception of the alarm call but could have caused non-specific alterations of vigilance behavior because of the presence of a loud noise. The experimental design was the same as in the sonic net trial described above except that we had a smaller sample size. Seven of the fourteen experimental flocks experienced a treatment sequence that started with a quiet control treatment followed by the sound treatment while the remaining seven flocks experienced a treatment sequence that began with the sound treatment followed by a quiet control treatment.

Analysis 2: Alarm call experiment.—We analyzed video from each trial for vigilance of the individual birds. We analyzed snapshots of the 60 seconds preceding and following the alarm call in each treatment for presence of vigilance behavior. We classified a bird as vigilant if it had its head above body level or perched on the side of the cage (Quinn et al. 2006).

In the two alarm call experiments we explored whether the birds' vigilance response to the playback of an alarm call was influenced by the presence of a sonic net (either at 2-10 kHz or at 0.1-2 kHz) by using a repeated measures ANOVA with both alarm call (pre-call compared with post-call) and sonic net (presence compared with absence) as within-group independent variables and percentage of time vigilant as the dependent variable. We further examined the relative effects of the alarm call on the vigilance of the birds by using paired t-tests of birds in the control (no sonic net) and sonic net situations, comparing

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their vigilance in the minute preceding and the minute following the playback of the alarm call.

In both the aviary and alarm call experiments the assumption of data sphericity (i.e., data are correlated) was violated in all repeated-measures ANOVAs therefore we interpreted Greenhouse-Geisser adjusted F-ratios. Percent data from the aviary experiment were arc-sine transformed to improve normality of residuals. All statistical analyses were performed with SPSS Statistics Version 20.0 (IBM Corp, Armonk, NY) employing two-tailed tests of probability.

3- RESULTS

a- Aviary experiment

Presence of the 2-10 kHz sonic net significantly deterred flocks of starlings from treated end of the aviary (Greenhouse-Geisser $F_{1,9}$ = 10.6, P = 0.010, partial eta-squared effect size = 0.540). On average, the proportion of time starlings were present was reduced by approximately 46% (Fig. 4). There was no general effect of day on the presence of birds at the food patches (Greenhouse-Geisser $F_{1.1,9.8}$ = 0.300, P = 0.616, partial eta-squared effect size = 0.032), nor was there a change in the effectiveness of the sonic net at deterring birds over the three days of the experiment (Greenhouse-Geisser $F_{1.2,11}$ = 2.67, P = 0.128, partial eta-squared effect size = 0.229).

The sonic net also reduced the number of starlings feeding at the affected food patches (Greenhouse-Geisser $F_{1,9}$ = 11.9, P = 0.007, partial eta-squared effect size = 0.570). On average, the number of feeding birds was reduced by 54% (Fig. 4). Consistent with the feeding data, there was less food eaten at the food patch affected by the sonic net (Greenhouse-Geisser $F_{1,9}$ = 8.73, P = 0.016, partial eta-squared effect size = 0.492). On average, weight of food eaten was reduced by 45% (Fig. 4). Day of the experiment did not influence the overall pattern of feeding by the birds (Greenhouse-Geisser $F_{1.1,9.8}$ = 1.32, P = 0.283, partial eta-squared effect size = 0.128), and the effect of the sonic net on deterring feeding did not change notably over the course of the experiment (Greenhouse-Geisser $F_{1.1,10}$ = 4.16, P = 0.065, partial eta-squared effect size = 0.316). Birds were still deterred on day 3 (t_9 = 2.77, P = 0.022). Although there was no general effect of day of experiment on the amount of food eaten (Greenhouse-Geisser $F_{1.1,9.9}$ = 2.17, P = 0.172, partial eta-squared effect size = 0.194) there was an indication that effectiveness of the sonic net at reducing the food eaten diminished over the three days of the experiment (Greenhouse-Geisser $F_{1.2,10.7}$ = 7.84, P = 0.015, partial eta-squared effect size = 0.466). Despite this reduction in effect on the amount of food eaten, there was still significantly less food eaten on the sonic net side of the aviary on day three compared with the control side (t_9 = 2.48, P = 0.035).

b- Alarm call experiment

Sonic net of 2-10 kHz.—The groups of starlings increased their vigilance following alarm call playback (Greenhouse-Geisser $F_{1,17} = 40.2$, $P \leq 0.00001$) (Fig. 5) and this response was reduced when birds were exposed to the 2-10 kHz sonic net (Greenhouse-Geisser $F_{1,17} = 32.6$, $P \leq 0.00003$). Specifically, when the sonic net was not applied (i.e. the control condition) the groups of starlings responded very strongly to the alarm call with increased vigilance behavior ($t_{17} = 6.69$, $P \leq 0.000005$). However, when the birds were exposed to the 2-10 kHz sonic net they did not show any vigilance response to the alarm call ($t_{17} = 0.914$, $P = 0.37$).

Sonic net of 0.1-2 kHz.—As before, the starlings showed increased vigilance in response to the alarm call (Greenhouse-Geisser $F_{1,13} = 45.9$, $P \leq 0.00002$) but unlike the 2-10 kHz treatment, the starlings did not have a reduced response when exposed to the 0.1-2 kHz sonic net (Greenhouse-Geisser $F_{1,13} = 5.97$, $P = 0.030$). As with the previous communication trials, the groups of starlings showed an increase in their vigilance in response to the alarm call when there was no sonic net over their cage ($t_{13} = 6.01$, $P \leq 0.00005$). When we applied the 0.1-2 kHz sonic net the birds still responded strongly to the alarm call playback by increasing their vigilance ($t_{13} = 3.81$, $P = 0.002$). Hence, the birds were able to perceive the alarm call and respond appropriately when exposed to the 0.1-2 kHz sonic net.

4- DISCUSSION

Our results indicate that the sonic net is effective at deterring starlings from food patches in an outdoor aviary over a three-day period. Our ability to displace starlings in cages over an extended period suggests that this technique may also be effective in the field. Starlings were continuously exposed to the sonic net for 8 hours a day for three consecutive days—a length of time sufficient for substantial learning and accommodation if the birds were able to adjust to the sonic net. We did not observe evidence that birds were less deterred on day 3 compared with day 1 of exposure to the sonic net. However, there was some indication that their food consumption recovered somewhat, but was still lower than in the reference treatment without the sonic net. This latter response in feeding but not occupancy may be an artifact of the birds having no predators in the aviary and birds learning that they could feed at a slightly faster rate without truly compromising their already altered predation risk.

The maintenance of the effect of the sonic net, we hypothesize, is because vocal communication is masked across such a broad range of auditory frequencies that there is little the starlings can do to avoid such masking. Some animals are capable of adjusting their vocalization to help avoid masking by background noise by increasing the amplitude (Brumm and Todt 2002, Brumm 2004) or frequency (Slabbekoorn and Peet 2003) of elements of their vocalizations. In these cases the amplitude and frequency shifts were much smaller than would be required to mitigate the masking effect of our sonic net. In communication systems, both the sender and receiver can adapt to noise

masking, but for important sounds the weight falls on the receiver (Barber et al. 2010) where vocal adjustment can come at a cost to both energy balance and information transfer (Barber et al. 2010). Future studies need to investigate the potential change in frequency and amplitude in the starling vocalizations and hence, will enable us to comment directly on whether the birds attempted to adjust their songs and calls in efforts to avoid acoustic masking.

The alarm call experiments support our general conclusions. The starlings did not respond to an alarm call when experiencing a sonic net that we hypothesized would mask the alarm call (i.e., the frequency range of 2-10 kHz). The absence of a response in this case can be due to the starlings not being able to perceive the alarm call when under the sonic net. However, they did respond when the sonic net was designed to not mask the alarm call (i.e., the frequency range of 0.1-2 kHz) and thus were able to perceive and respond to the alarm call. Therefore, we conclude that the sonic net that we applied in the aviary trials (2-10 kHz) likely masked auditory communication for starlings, which we hypothesize, led to an increase in perceived predation risk of the affected area and, hence, decreased occupancy and feeding efficiency by the birds.

We are not the first to indicate that a bird species can be largely excluded from an area dominated by noise. The relatively low frequency environmental noise produced by natural gas drilling platforms restructures entire bird communities by driving off certain species and favoring others (Francis et al.

2011). However, to the best of our knowledge, we are the first to use a spatially controlled noise that is designed to mask acoustic communication to deter a pest avian species over a period of three days. Many of the current technologies used to deter pest birds lose their effectiveness very quickly (Bomford and O'Brien 1990) but our solution maintains its effectiveness in displacing starlings despite several days of consecutive intense exposure in captivity. Further, as our experiments indicate that the 2-10 kHz sonic net masks communication of perceived danger, and likely increases perceived predation risk we predict that the effectiveness of this sonic net will be greater in field conditions compared with our aviary trials. In the aviary, birds were not exposed to real predation threats whereas birds' inability to detect predators reliably will carry greater costs in nature.

Our sonic nets may be particularly effective at excluding starlings because starlings form large flocks (Morrison and Caccamise 1990, Caccamise 1991) where foraging success and the probability of food discovery can be increased by vocal communication within the flock (Clark and Mangel 1984, Giraldeau 1984). Sharing information about foraging success benefits the birds in that it reduces the searching time and leads to an increase in individual foraging rates (Caraco 1981, Clark and Mangel 1984, Templeton and Giraldeau 1995). Birds that are unable to communicate tend to forage less efficiently as they are unable to share information about predators and thus have to spend more time vigilant instead of foraging. This hypothesis is supported by the results from our alarm

call experiments. Additionally, we hypothesize that perceived predation risk is increased when birds are less able to rely on audible messages that relay information about predatory threats, such as alarm calls or sounds emitted directly by predator species themselves (Klump and Shalter 1984, Gyger et al. 1986, Smith 1986).

At a time when anthropogenic noise pollution affects wildlife populations (Brumm and Slabbekoorn 2005, Barber et al. 2010), the results from this study can also help us better understand how and why bird communities are affected by chronic noise. We predict that with increasing frequency (pitch) of noise pollution we will see greater disturbance of behaviors mediated by vocal communication, such as foraging and anti-predatory behaviors. Decreased foraging and increased perceived predation risk, in such situations, will likely results in lower individual and population fitness. The sonic net likely induces a change in the birds' perception of risk as it prevents them from relying on auditory cues to detect predators. Free-living birds that cannot forage efficiently and are subject to a reduced ability to detect predators will likely suffer an overall loss of fitness (Klump 1996, Kight and Swaddle 2011, Kight et al. 2012) that could be compensated for by moving to acoustically more suitable environments.

Here we propose a novel system for excluding European starlings from habitats that have high potential for human-wildlife conflict such as airports, agricultural fields, and other socio-economically important areas. Our method

capitalizes on the critical importance of vocal communication. We used highly directional speakers to produce a contained net of sound that masks auditory communication and renders the treated area acoustically unsuitable without causing noise pollution in the surrounding area. In controlled aviary conditions we reduced the presence of starlings by 46%, on average, but we predict the magnitude of this effect may be larger in the field when birds face real predation threats. We are in the process of commencing field tests to gauge the effectiveness of our sonic nets at excluding pest birds in less controlled situations. At this stage we have yet to investigate the effects of the sonic net on non-target species but this will be incorporated as part of the study design in our ongoing field tests. It may be possible that some species are more sensitive to masking in particular frequency ranges, which may help us in designing sonic nets that exclude particular species from socio-economically important areas.

APPENDIX

Flock Number	Day	Reference % birds	Treatment % birds	Reference % feeding	Treatment % feeding	Reference % eaten	Treatment % eaten
1	1	85.9	10.2	75	2.1	88.7	13.7
1	2	14.1	50.3	25	36.8	11.3	36.2
1	3	14.1	3.9	25	0	11.3	5.5
2	1	79.5	66	80.6	69.9	82.6	75.3
2	2	20.5	9.96	19.4	6.52	17.4	17.6
2	3	20.5	23.6	19.4	26.4	17.4	30
3	1	63.3	2.78	68.6	2.15	70.7	4.18
3	2	36.7	14.9	31.4	11.8	29.3	16.2
3	3	36.7	5.52	31.4	5.35	29.3	7.9
4	1	78.5	7.2	70.7	6.8	78	7.2
4	2	21.5	16.4	29.3	11.9	22	11
4	3	21.5	17.8	29.3	21.8	22	12.2
5	1	91.6	4.5	98.5	1.8	92.7	9
5	2	8.4	3.7	1.5	0	7.3	6.5
5	3	8.4	12.2	1.5	6.1	7.3	9.4
6	1	70.4	0.8	87.8	0	74.2	1.5
6	2	29.6	3.5	12.2	0	25.8	4.2
6	3	29.6	1.6	12.2	1.4	25.8	2.5
7	1	43.2	34.7	45.7	19.2	49.2	22.4
7	2	56.8	73.7	54.3	76.8	50.8	77.4
7	3	56.8	76.9	54.3	80	50.8	79
8	1	9.9	0	12.3	0	15.8	2.19
8	2	90.1	6.03	87.7	0	84.2	8.09
8	3	90.1	14.1	87.7	10.6	84.2	23
9	1	9.11	5.92	29.1	15.2	51.3	18.3
9	2	90.9	58.8	70.9	19.2	48.7	27.5
9	3	90.9	69.1	70.9	26.7	48.7	32.2
10	1	76.6	64.8	80	46.9	68.4	50.8
10	2	23.4	20.6	20	35.4	31.6	37.3
10	3	23.4	65.2	20	71.7	31.6	76.8

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FIGURE LEGENDS

Figure 1. Plan view of the aviary experimental area. Circles (A) and (B) indicate food patches. Rectangle (W) indicates water dish.

Figure 2. Schematic of the aviary experiment. (A) and (B) indicate food patches (Fig. 1). For half of the flocks the sonic net was applied in a BAA treatment sequences whereas the other half of the flocks were subject to an ABB treatment sequence. Both sequences were preceded by an aviary acclamation day and a reference day with no sonic net treatment.

Figure 3. Schematic of the alarm call experiment timeline. Visual representation of a single trial where (Treatment 1) and (Treatment 2) are either "sonic net" or "quiet" treatment. Bracketed areas indicate pre- and post-alarm call data collection time intervals.

Figure 4. Effects of the sonic net in the aviary experiment. All values are mean ± standard error. (A) Reduction in the % birds present under the sonic net when compared with the same area under a no sound treatment. (B) Reduction in the % birds feeding under the sonic net when compared with the same area under a no sound treatment. (C) Reduction in the % amount food eaten under the sonic net when compared with the same area under a no sound treatment.

Figure 5. Mean (± standard error) percent time spent vigilant through different stages of the alarm call experiment. (A) There was no increase in vigilance to the broadcast of an alarm call when under a 2-10 kHz sonic net. (B) There was an increase in vigilance in response to the broadcast of an alarm call when under a 0.1-2 kHz sonic net.
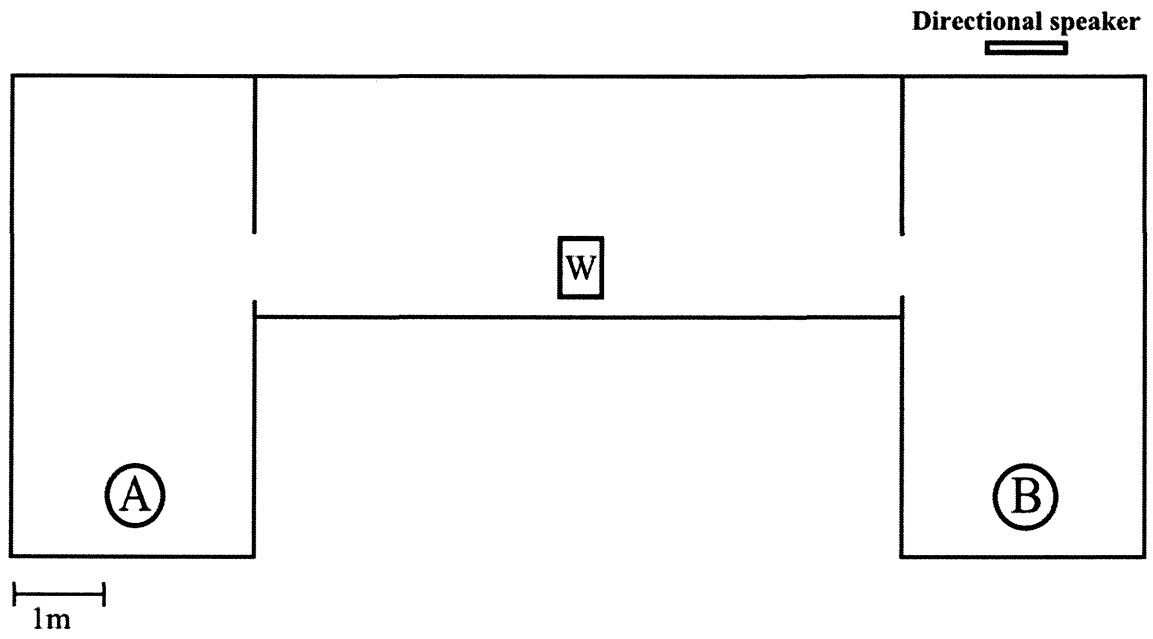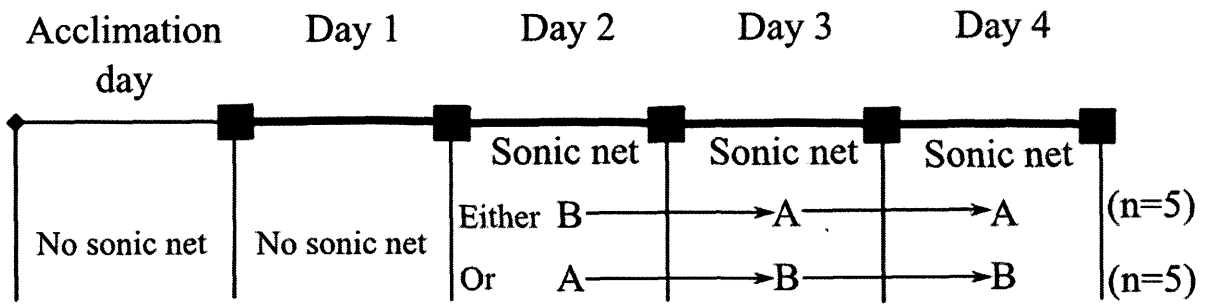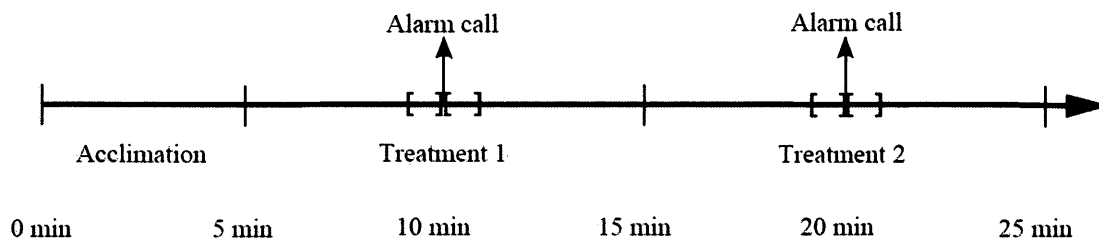
Figure 1.

Directional speaker

W

Ⓐ

Ⓑ

1m

Figure 2.

Acclimation day | Day 1 | Day 2 | Day 3 | Day 4

No sonic net | No sonic net | Sonic net | Sonic net | Sonic net

Either B ——→ A ——→ A (n=5)

Or A ——→ B ——→ B (n=5)

Figure 3.

Alarm call   Alarm call

| Acclimation | Treatment 1 | Treatment 2 |

0 min   5 min   10 min   15 min   20 min   25 min
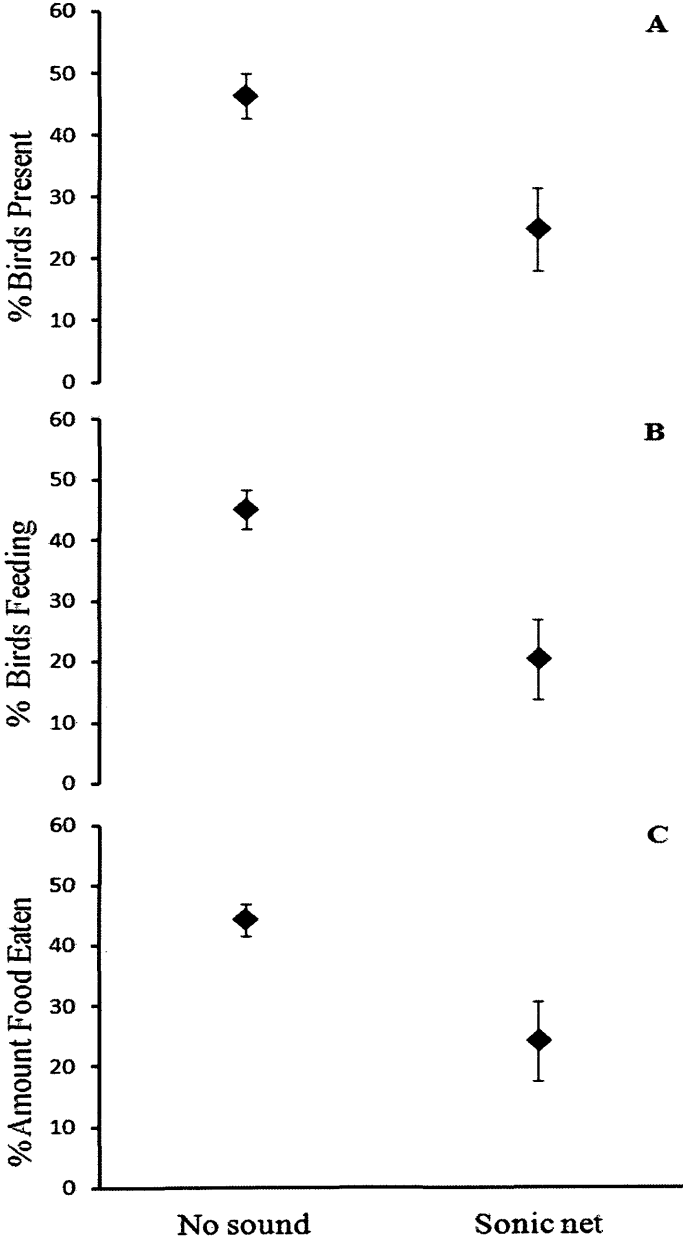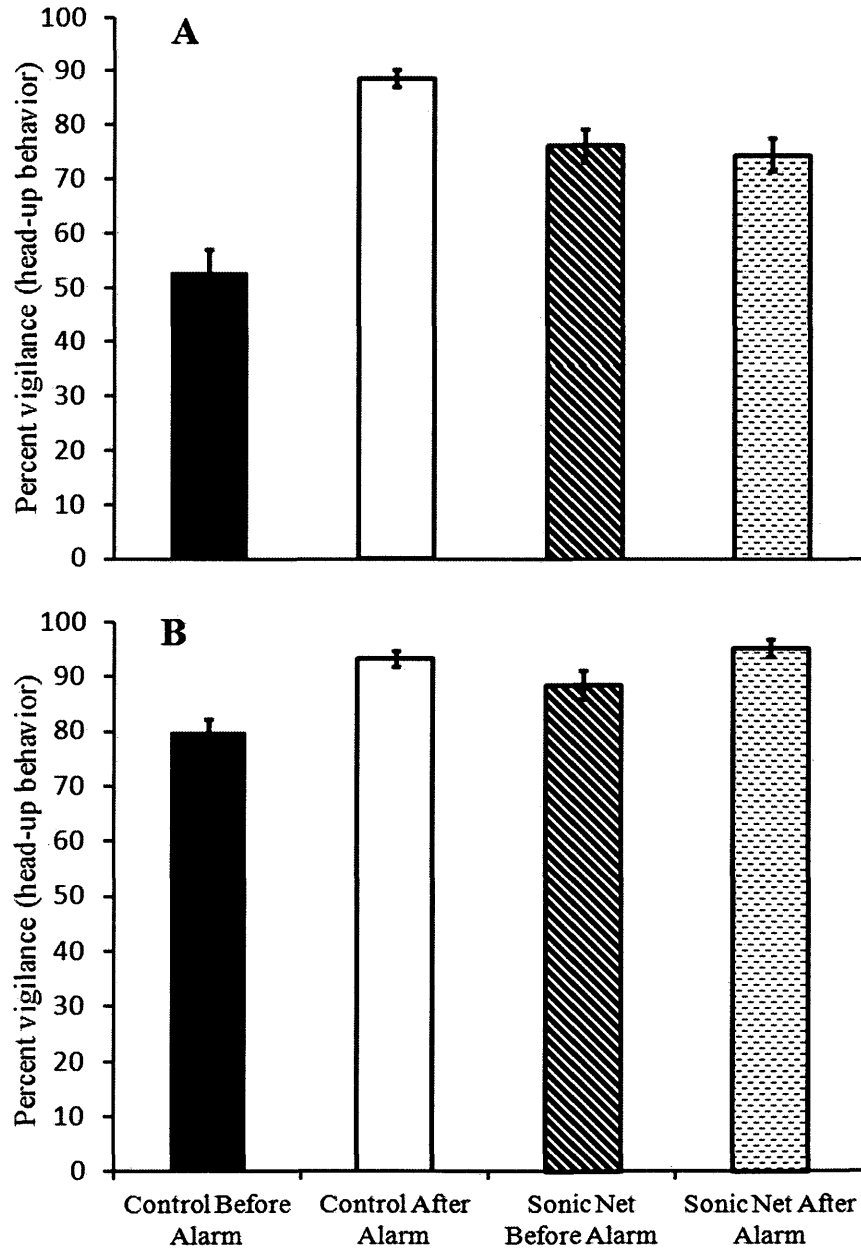
Figure 4.

Figure 5.

VITAE

Education

College of William and Mary, Williamsburg VA   Expected May 2014

MS Biology

Thesis title: Using a "sonic net" to deter pest bird species: excluding European starlings from food sources by disrupting their acoustic environment.

Virginia Polytechnic Institute and State University, Blacksburg VA   May 2012   *BS Biology*

Publications

Mahjoub G, Hinders MK, and Swaddle JP. Using a "sonic net" to deter pest bird species: excluding European starlings from food sources by disrupting their acoustic communication. Wildlife Society Bulletin 2014. (Submitted January 2014)

Dieckman EA, Skinner E, Mahjoub G, Swaddle JP, and Hinders MK. Benign exclusion of birds using acoustic parametric arrays. Proceedings of Meetings on Acoustics, Vol. 19, 010063 (2013) DOI: 10.1121/1.4801408 (June 2013)

Grants

NASA Virginia Space Grant Consortium Graduate Fellowship   Spring 2013

Arts and Sciences Graduate Research Grant, College of William and Mary Spring/Fall 2013

Williamsburg Bird Club Student Research Grant   Spring 2013

Honors and Awards

Carl J. Strikwerda Award for Excellence in the Natural and Computational Sciences, College of William and Mary   March 2014

Outstanding Teaching Assistant Award, College of William and Mary   Fall 2013

Ralph E. Carlson Memorial Scholarship in Ornithology, Virginia Tech   Fall 2010-Spring 2012