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Now Hear This! Orientation and Behavioral Responses of Hatchling Loggerhead Sea Turtles, Caretta caretta, to Environmental Acoustic Cues

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Description

Although the visual and geologic orientation cues utilized by sea turtle hatchlings during seafinding, when they move from the nest to the sea after hatching, have been well studied, the potential for auditory stimuli to act as an orientation cue has not been well explored. Over the past several decades our knowledge of the auditory capacity of sea turtles has increased greatly, yet little is known about the biological significance of this sensory ability. To investigate whether hatchlings can use ocean sounds during seafinding, we measured the behavioral responses of hatchling loggerhead sea turtles (Caretta caretta) collected from nesting beaches in North Carolina to the presence of beach wave sound recorded on a nesting beach during the summer of 2015. The highest sound energy of beach waves occursHz, which overlaps with the most sensitive hearing range of loggerhead hatchlings (range of frequency detection: 50-1600 Hz, maximum sensitivity: 50-400 Hz). In our experiment, we placed turtles in a V-maze that isolated them from visual, vibratory, and chemical cues. One end of the V held a speaker producing beach wave sounds recorded from nesting beaches, while the other end held sound-reducing foam. We examined the phonotaxic behaviors of the hatchlings at two sound pressure levels (68 dB re: 20μPa and 64 dB re: 20μPa measured directly in front of the speaker). In the presence of the higher sound pressure level (68 dB re: 20μPa), hatchlings exhibited no phonotaxic response ($p=1.0$); yet, at the reduced sound pressure level (64 dB re: 20μPa), hatchlings exhibited a negative phonotaxic response ($p=0.005$). In control trials, hatchlings oriented to the two sides of the V-maze equally ($p=0.701$), suggesting the hatchlings in the lower volume treatment group were responding negatively to the sound. These results indicate the need for further auditory orientation experiments to better understand hatchling behavioral responses to environmental acoustic cues and to address possible impacts of anthropogenic beach sounds that have the potential to disorient hatchlings during seafinding.

Location
CUB Ballroom

Disciplines
Animal Sciences | Aquaculture and Fisheries | Environmental Monitoring | Environmental Sciences | Environmental Studies

Comments
Environmental Studies Senior Honors Thesis

Attached is the full research thesis, which the poster presentation was based on.

Now hear this! Orientation and behavioral responses of hatchling loggerhead sea turtles,
***Caretta caretta,* to environmental acoustic cues**

Bethany Holtz

ES 460-Honors Thesis
Environmental Studies Department
Advisor: Dr. Wendy Dow Piniak
Second Reader: Dr. Peter Fong

Abstract

Although the visual and geologic orientation cues utilized by sea turtle hatchlings during seafinding, when they move from the nest to the sea after hatching, have been well studied, the potential for auditory stimuli to act as an orientation cue has not been well explored. Over the past several decades our knowledge of the auditory capacity of sea turtles has increased greatly, yet little is known about the biological significance of this sensory ability. To investigate whether hatchlings can use ocean sounds during seafinding, I measured the behavioral responses of hatchling loggerhead sea turtles *(Caretta caretta)* collected from nesting beaches in North Carolina to the presence of beach wave sound recorded on a nesting beach during the summer of 2015. The highest sound energy of beach waves occurs <1000 Hz, which overlaps with the most sensitive hearing range of loggerhead hatchlings (range of frequency detection: 50-1600 Hz, maximum sensitivity: 50-400 Hz). In my experiment, I placed turtles in a V-maze that isolated them from visual, vibratory, and chemical cues. One end of the V held a speaker producing beach wave sounds recorded from nesting beaches, while the other end held sound-reducing foam. I examined the phonotaxic behaviors of the hatchlings at two sound pressure levels (68 dB re: 20μPa and 64 dB re: 20μPa measured directly in front of the speaker). In the presence of the higher sound pressure level (68 dB re: 20μPa), hatchlings exhibited no phonotaxic response (p=1.0); yet, at the reduced sound pressure level (64 dB re: 20μPa), hatchlings exhibited a negative phonotaxic response (p=0.005). In control trials, hatchlings oriented to the two sides of the V-maze equally (p=0.701), suggesting the hatchlings in the lower volume treatment group were responding negatively to the sound. These results indicate the need for further auditory orientation experiments to better understand hatchling behavioral responses to environmental acoustic cues and to address possible impacts of anthropogenic beach sounds that have the potential to disorient hatchlings during seafinding.

Introduction

Concern over the ecological and biological effects of pollution and anthropogenic activity in coastal and oceanic marine habitats has risen to the forefront of academic, political, and social discussions over the last several decades (Howard and Griffis 2013, Chasek et al. 2014, Hamilton and Saffirs 2015). Despite this concern, human population in coastal areas continues to grow, increasing the prevalence and intensity of human disturbances (Aguirre and Lutz 2004, Schlacher et al. 2007). For this reason, it is pertinent to understand how human presence in these ecologically important areas impacts threatened and endangered wildlife.

One such affected species is the loggerhead sea turtle, *Caretta caretta*. Loggerhead sea turtles are currently listed as threatened under the Endangered Species Act and vulnerable on the International Union for Conservation of Nature (IUCN) Red List (NOAA 2014, Casale and Tucker 2015). They are also protected by numerous international laws and treaties, including the Convention on International Trade in Endangered Species of Wild Flora and Fauna (CITES), Convention on Migratory Species (CMS), Specially Protected Areas and Wildlife Protocol (SPAW) and Inter-American Convention for the Protection and Conservation of Sea Turtles (IAC) (Bolten and Witherington 2003, NOAA 2014). Loggerheads inhabit the coastal beaches and oceanic and neritic zones of the Atlantic, Pacific, and Indian Oceans (Lutz and Musick 1997, Bolten and Witherington 2003, NOAA 2014). Beach environments play a pivotal role in the sea turtle life cycle, especially for females in the process of nesting and hatchlings beginning their life journey (Lanyon et al. 1989, Lutz and Musick 1997, Fig. 1). The majority of loggerhead nesting occurs along the coastal areas of the Atlantic and Indian Oceans, with south Florida (U.S.) and Masirah Island (Oman) being the only two nesting areas to currently have greater than 10,000 nesting females (NOAA 2014). As coastal development continues to threaten natural

beach habitat, population recovery of loggerheads becomes particularly difficult as both

hatchling survival and female nesting along beaches play a pivotal role in reproduction and

population dynamics (Lutz and Musick 1997, Bolten and Witherington 2003). Moreover,

loggerhead sea turtles exhibit a high degree of nest site fidelity with hatchling returning to the

region of their birth (or natal beaches), and adult females often renest within 5 km each

subsequent nesting season, making beach protection of utmost importance to loggerhead

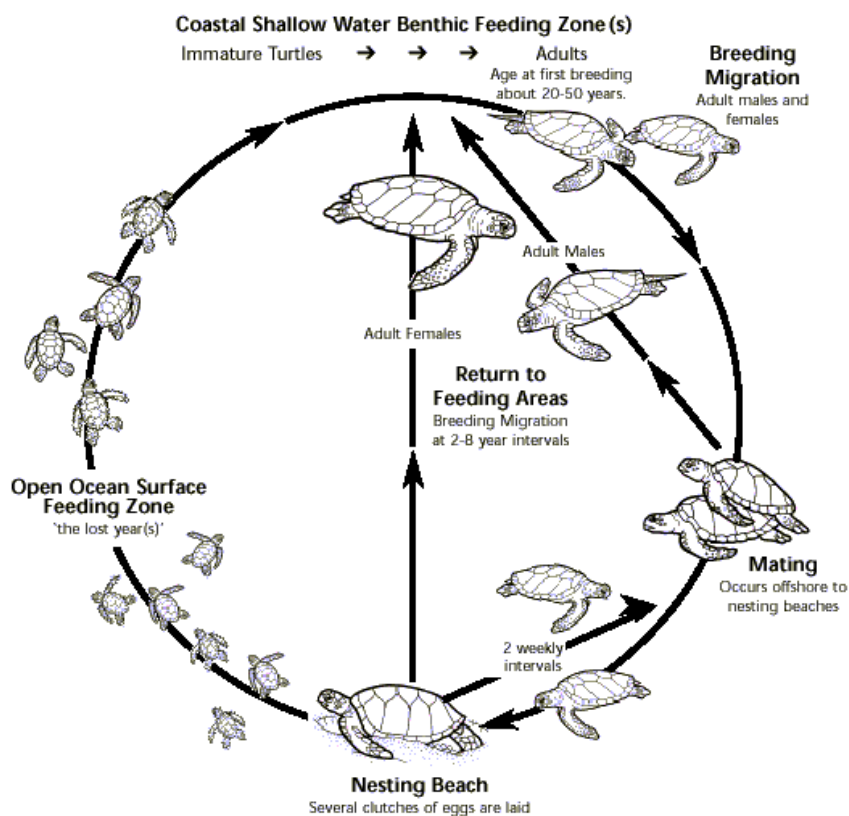population recovery (Lutz and Musick 1997).

Figure 1. Life cycle of loggerhead sea turtles, *Caretta caretta* (Lanyon et al. 1989).

Coastal development can greatly impact survival of hatchlings in particular, as they rely heavily upon environmental cues to orient toward and find the ocean. Previous research has shown that visual cues play a large role in "sea-finding" in hatchlings (Carr and Ogren 1960, Mrosovsky and Shettleworth 1968, Salmon and Wyneken 1994). Once they have emerged from their nests, hatchlings orient towards the lowest, brightest horizon, away from dunes and vegetation and towards the broad-open horizon where starlight, moonlight, and sunlight is reflected on the ocean's surface (Mrosovsky and Shettleworth 1968, Salmon and Wyneken 1994, Lutz and Musick 1997). Coastal development along beaches can eliminate, alter, or conflict with these natural stimuli utilized by sea turtles for orientation and other behavioral practices (Lutz and Musick 1997, Rivas et al. 2015). Research, thus far, has focused on the implications of light pollution on hatchling, juvenile, and adult female nesting behavior. Artificial illumination on nesting beaches has been shown to alter both hatchling behavior and female nesting due to disorientation (Witherington et al. 1990, Kamrowski et al. 2012, Rivas et al., 2015). Artificial lighting oriented toward the land may attract or disorient hatchlings by providing more intensive or conflicting light stimuli. This disorientation leads to a delayed sea finding and possible death due to dehydration, exhaustion or predation (McFarlane 1963, Philibosian 1976, Magyar 2008).

While previous research has shown sea turtles respond to and perceive a variety of visual cues that are altered by coastal development, as well as magnetic and chemical cues present in their environment, little is known about how they respond to acoustic cues present in their environment (e.g. visual: Crognale et al. 2008, Wang et al. 2007, Wang et al. 2010, Young et al. 2012; magnetic: Lohman et al. 2001, Avens et al. 2003, Lohmann et al. 2004, Fuxjager et al. 2011; chemical: Manton et al. 1972, Owens et al. 1982, Grassman and Owens 1987, Endres et al. 2012) . While there is little evidence that sea turtles produce or use sound for communication,

they are able to detect (Ridgway et al. 1969, Bartol et al. 1999, Bartol and Ketten 2006, Martin et al. 2012, Piniak 2012, Lavender et al. 2014) and respond to low-frequency acoustic stimuli (O'Hara and Wilcox 1990, McCauley et al. 2000, Weir 2007, Hazel et al. 2009, DeRuiter and Doukara 2012). Though systematic measurements of the levels of ambient sound around the globe are lacking, it is generally agreed that levels of anthropogenic sound are becoming more widespread and intense, increasing the need for studies of potential impact of anthropogenic sound on sea turtles (Ross 1993, McCauley et al. 2000, Andrew et al. 2002, Hildebrand 2009).

Sea turtles hear through a vertebrate tympanic middle ear path: a tympanum connected to facial tissue, an air-filled middle ear cavity, and a connection to the inner ear via a single middle ear bone (Wever and Vernon 1965, Wever 1978, Lenhardt et al. 1985). Early studies measured the hearing potential in sea turtles by recording cochlear response potentials of the inner ear to aerial and vibrational stimuli, finding that juvenile green turtles (*Chelonia mydas*) responded to tonal stimuli in air measuring 50 to 2,000 Hz and vibrational stimuli between 30 and 700 Hz (Ridgway et al. 1969). More recent studies measured hearing sensitivity by recording auditory evoked potentials (AEPs), or electrical responses produced by the central auditory nervous system after sound stimulation detectable by the ear (Yost 2007, Au and Hastings 2008). Studies measuring the hearing range of juvenile green, hatchling hawksbill (*Eretmochelys imbricata*), and hatchling leatherbacks (*Dermochelys coriacea)* in both air and water revealed that sea turtles can detect low-frequency aerial and underwater acoustic signals between 50-1600Hz with maximum sensitivity between 100-400Hz (Piniak 2012). Looking specifically at loggerheads, Bartol et al. (1999) measured short latency AEPs in juveniles in response to low-frequency clicks and tone bursts delivered via vibration to the tympanum. They found an effective hearing range from tone bursts from 250 to 750 Hz with maximum sensitivity at 250 Hz, the lowest frequency

tested (Bartol et al. 1999). Underwater studies of loggerhead hearing revealed a post-hatchling

and juvenile hearing frequency range of 50-1000/1100 Hz and a maximum sensitivity between

100-400 Hz using both AEPs and behavioral trials (Lavender et al. 2014). Using similar

methodologies, Martin et al. (2012) also found that adult loggerheads have a peak sensitivity

between 100 and 400 Hz underwater. Unpublished measurements of aerial hearing in hatchling

loggerhead sea turtles show sound detection between 50 and 1600 Hz with maximum sensitivity

between 50 and 400 Hz (Piniak unpublished data, Fig. 2). Low-frequency sounds inside these

tonal detection ranges include anthropogenic sounds produced by airplanes, sonar, shipping, oil

and gas exploration and extraction, and other anthropogenic sources, as well as natural

environmental acoustic stimuli including wave and wind sounds (Richardson et al. 1995, Piniak
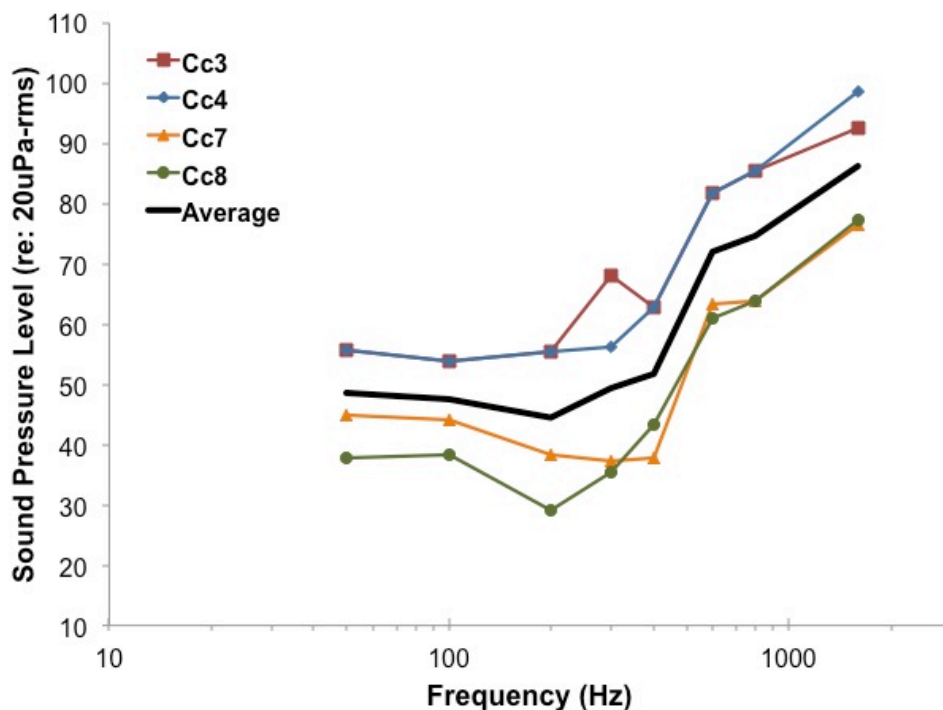
2012).

Figure 2. Aerial audiograms for four hatchling loggerhead sea turtles, *Caretta caretta* (Piniak unpublished data).

While our understanding of sea turtle detection and response to sound has increased greatly over the last decade, the biological significance of sound for sea turtles remains mostly unknown. It is hypothesized that turtles may use sound in navigation, prey location, predator detection and avoidance, and for general environmental awareness (Piniak 2012). Studies beginning to examine the physiological and behavioral impacts of sound have been limited to sea turtle underwater responses to explosions and seismic airguns (O'Hara and Wilcox 1990, Moein et al. 1994, McCauley et al. 2000, Weir 2007, Hazel et al. 2009, DeRuiter and Doukara 2012). In the presence of both explosions and seismic airguns, sea turtles exhibited notable behavioral responses, including erratic swimming and diving behavior, indicating sensitivity to changes in sound pressure (O'Hara and Wilcox 1990, Moein et al. 1994, McCauley et al. 2000, Weir 2007, Hazel et al. 2009, DeRuiter and Doukara 2012).

Survivorship of hatchlings is critical to increasing population levels of endangered and threatened sea turtles, making the understanding of how hatchlings respond to environmental and anthropogenic noise along beaches a pinnacle in conservation efforts. To understand the implications of anthropogenic noise on sea turtles, we must first understand how they use natural sounds as behavioral cues. As studies examining sea turtle behavioral responses to sound have been limited, and studies exploring responses to natural environmental acoustic cues and aerial cues are completely lacking, this study aims to begin to investigate how sea turtles might use acoustic stimuli present in their environment. Specifically, this study aims to investigate the potential for natural beach sounds (sounds of waves) to act as an orientation cue for hatchlings during sea-finding. It was hypothesized that hatchling loggerhead sea turtles would orient toward wave sounds, in the absence of all other visual, chemical, vibratory, and other environmental cues (slope, etc.).

Methods

Sea Turtle Hatchlings

In late summer of 2015, I collected hatchling loggerhead sea turtles from three nesting beaches along Fort Fisher and Kure Beach in North Carolina. Hatchlings were collected as they emerged from their nests and transported in dark buckets to the testing facility. I kept the hatchlings in dark buckets to ensure they were unexposed to any visual orientation cues. I conducted all trails just after hatching, during a time when hatchlings are normally engaged in sea-finding behavior. Each hatchling participated in a single trail and was released the same night before sunrise. I measured curved and straight carapace width and length, as well as the weight of each hatchling for morphometric data comparison using standard methodology (National Marine Fisheries Service 2008).

Sound Recording and Generation

In front of a nest on Fort Fisher beach, I made several recordings of wave sounds using an Earthwork's M20BX microphone covered with a wind screen protector and a M-Audio MicroTrack II Digital Recorder. The digital recorder was set to record wave files at a sample rate of 96kHz. In the lab, I transferred the wave file to a Tascam DR-05 Digital Recorder and used a Definitive Technology DI 6.5 R speaker amplified by a Samson Servo 120A amplifier to play the wave signal. I measured the sound pressure level to ensure the volume was loud enough for hatchlings to hear based on available audiograms (Fig. 3). The highest sound energy of beach waves occurs <1000 Hz, which overlaps with the most sensitive hearing range of loggerhead hatchlings (range of frequency detection: 50-1600 Hz, maximum sensitivity: 50-400 Hz).
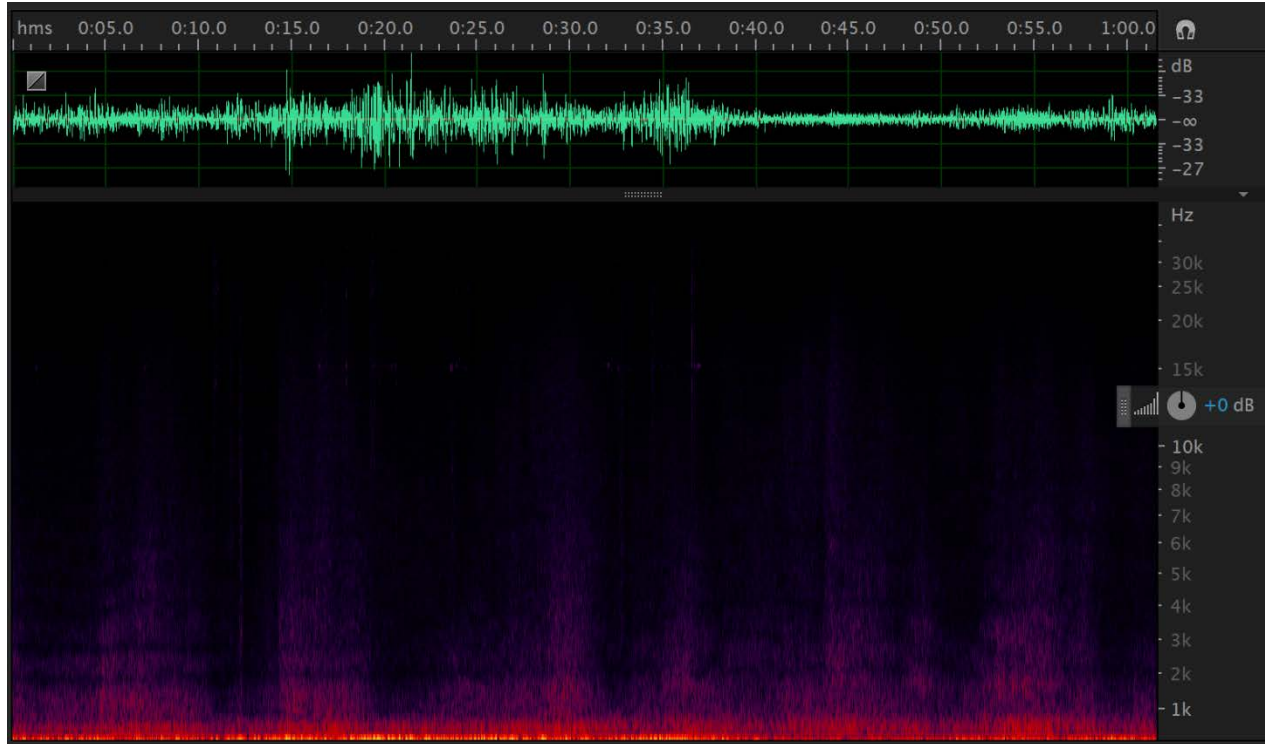
Figure 3. Spectogram of the recorded wave sound presented to the loggerhead sea turtle hatchlings.

Experimental Design

       I tested the turtles in a light-tight V-shaped maze (32 x 10 x 10 inches) following the

protocols presented by Witherington and Bjorndal (1991) for similar experiments examining

behavioral responses and orientation of hatchlings to visual cues in air (Fig. 4). The V-maze was

oriented in the room so that the ends of the maze were pointed toward the eastern beach in order

to control for geographic orientation cues. One end of the V held a speaker producing the sounds

of beach waves, while the other end held sound-reducing foam. To minimize sound reflections

from the sound side of the maze, I encased the V-maze in two inch Auralex Studiofoam Wedge-

22 sound-reducing foam (NRC Rating=0.80). I placed turtles into the middle of the V and gave

them 5 minutes to crawl toward or away from the sound. At the end of both the sound and no-

sound end side of the V-maze were collection pitfall pockets made of black light-proof fabric

created for the turtles to fall into after they had chosen to crawl to a particular side of the maze in

order to determine when the hatchlings reached the end. If the hatchlings did not fall into either

pitfall during the five-minute test period, I opened up the arena and determined the location of
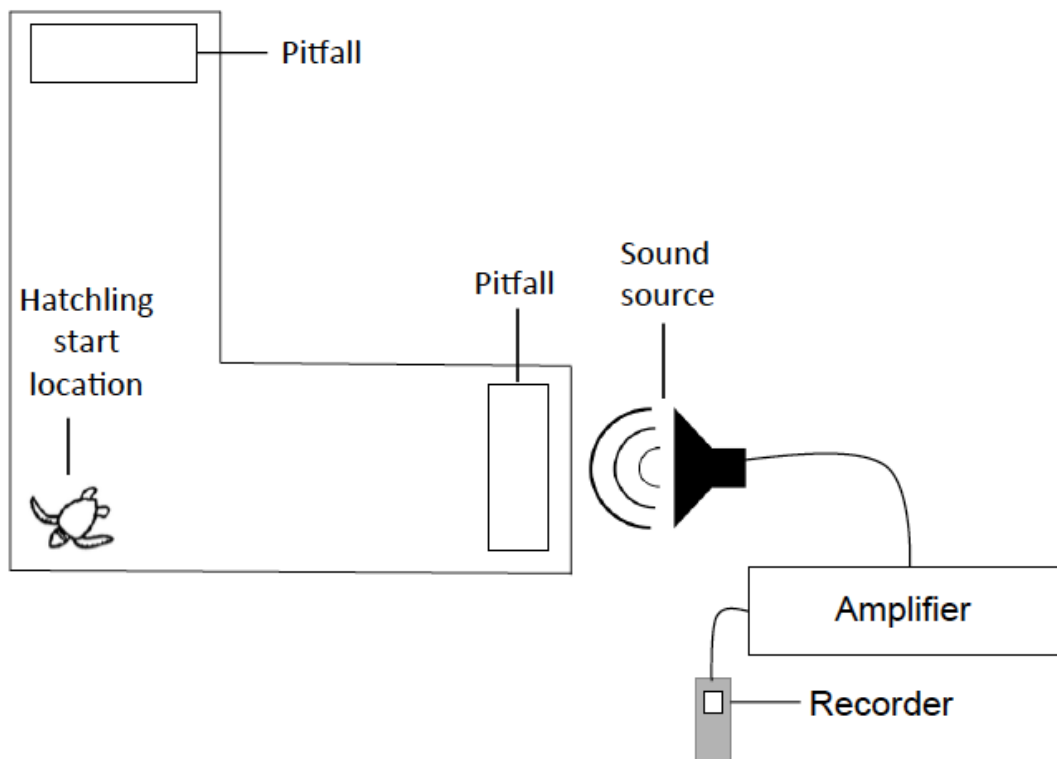
the hatchling.

Figure 4. V-maze arena (diagram modified from Witherington and Bjorndal, 1991).

I examined the phonotaxic behaviors of the hatchlings at two sound pressure levels (68 dB re: 20µPa and 64 dB re: 20µPa, measured directly in front of the speaker). To reduce biases, I alternated the sound and no sound side of the maze between trails, and to ensure hatchlings did not exhibit preference for one side of the maze I conducted control trials in which the speaker was present, but no sound was played during the trial. I tested 32 turtles in the control trial, 33 turtles at the higher sound pressure level and 30 turtles at the lower sound pressure level.

Using the Earthwork's M20BX microphone and M-Audio recorder I measured and mapped the sound field at several points throughout the testing arena (Fig. 5). To estimate the sound field at all points throughout the arena, an inverse distance weighted interpolation was conducted in ArcGIS Geostatistical Analyst (Fig. 6). The optimal power value was determined using a Kriging model through cross-validation.
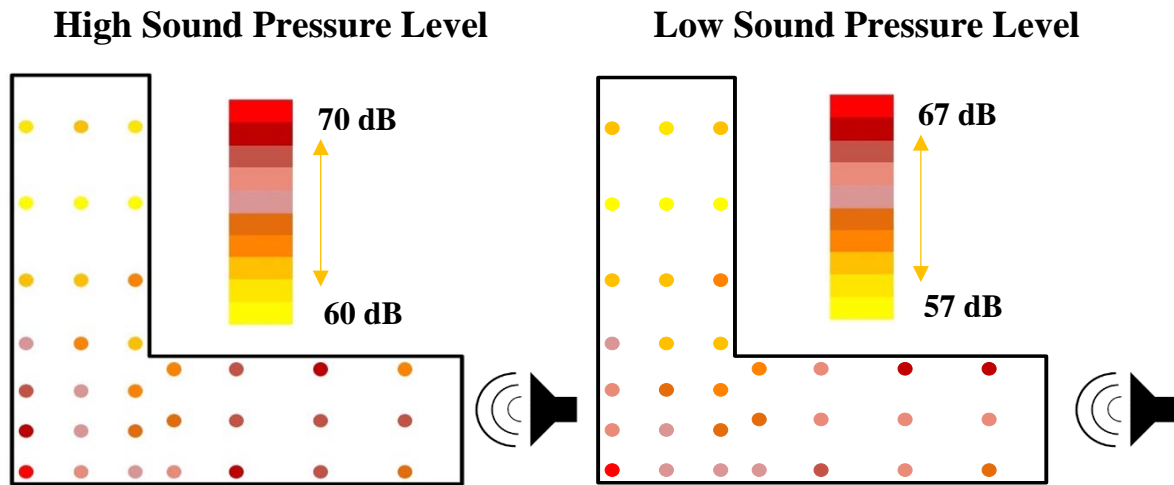
High Sound Pressure Level   **Low Sound Pressure Level**

Figure 5. Average RMS sound levels measured inside the V-maze in dB re: 20μPa. Range of levels from the high sound pressure trial (left–68 dB re: 20μPa, mean: 65.7dB) and low sound pressure trial (right–64 dB re: 20μPa, mean: 62.1 dB) are shown using a gradient color scale. Levels were divided into ten groups by half a standard deviation. Scale levels vary by a 1.2 dB.

High Sound Pressure Level   **Low Sound Pressure Level**
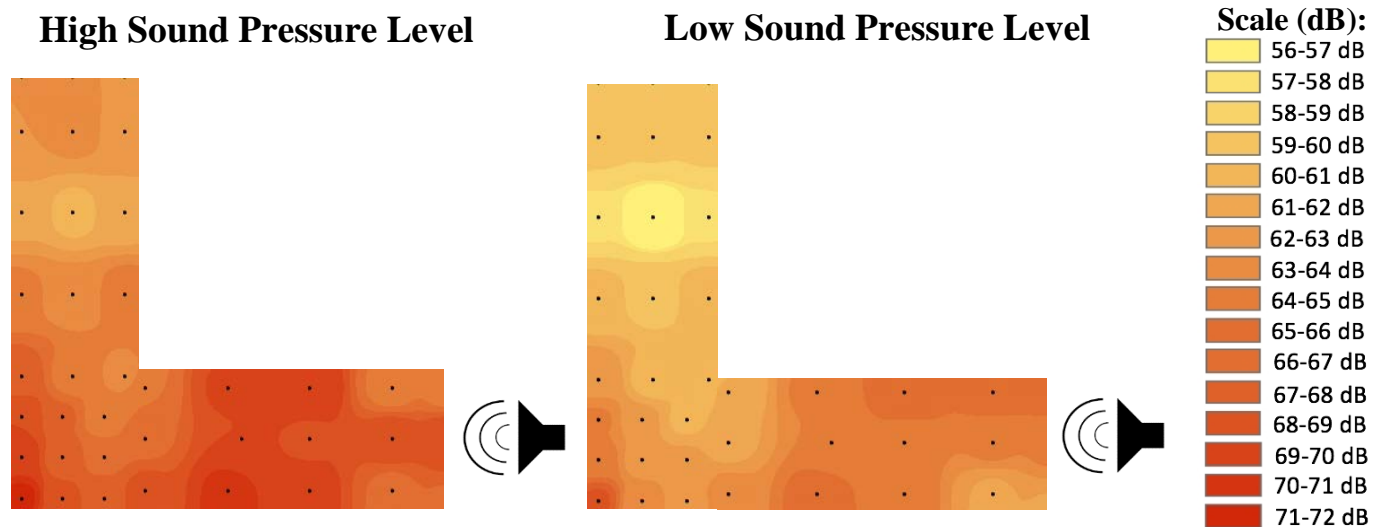
Figure 6. Sound field measured inside the V-maze in dB re: 20μPa. Range of levels from the high sound pressure trial (left–68 dB re: 20μPa) and low sound pressure trial (right–64 dB re: 20μPa) are shown using a gradient color scale. Average RMS sound pressure levels were recorded at set points (shown as black dots) and then imported into ArcGIS Geostatistical Analyst where an inverse distance weighted interpolation was conducted to estimate the values in between. The optimal power value for the interpolation was determined using a Kriging model through cross-validation.

Statistical Analysis

I analyzed the trial data using a binomial test conducted in SPSS to look at differences in the proportion of turtles that moved towards both high sound volumes and low sound volumes compared to those of the control trial. I specified the α level at $\alpha = 0.05$ to test whether the proportion of turtles in each category (movement towards sound compared to movement away from the sound) was different from 0.5 (no preference) in each of the trial groups. Hatchlings that did not reach the collection pitfalls at the conclusion of the five-minute test period were excluded from the statistical analysis for all trail groups.

Results

Hatchlings averaged 18.9 g in weight (range: 13.5 – 22.3 g), 47.4 mm in curved carapace length (range: 32 – 53 mm), 44.6 mm in curved carapace width (range: 32 – 52 mm), 45.4 mm in straight carapace length (range: 35 - 48.9 mm) and 34.5 mm in straight carapace width (range: 25 - 38.4 mm).

Of the 95 hatchlings tested, less than 10% (9 turtles) failed to orient to either side of the V-maze within the 5-minute allotted time. Hatchlings that did orient within the maze did so at an average of 104 ± 66 seconds, with 53% orienting in less than two minutes and 83% orienting in less than three minutes.

In control trials, hatchlings did not exhibit a preference for either side of the V-maze (p=0.701) (Fig. 7A). In the presence of the higher sound pressure level (68 dB re: 20μPa), hatchlings exhibited no phonotaxic response (p=1.0) (Fig. 7B). At the reduced sound pressure level (64 dB re: 20μPa), hatchlings exhibited a negative phonotaxic response (p=0.005) (Fig. 7C).

(A)

**Control Trial
(No Sound)**

(B)

**High Sound Pressure Level
(68 dB re: 20µPa)**

(C)

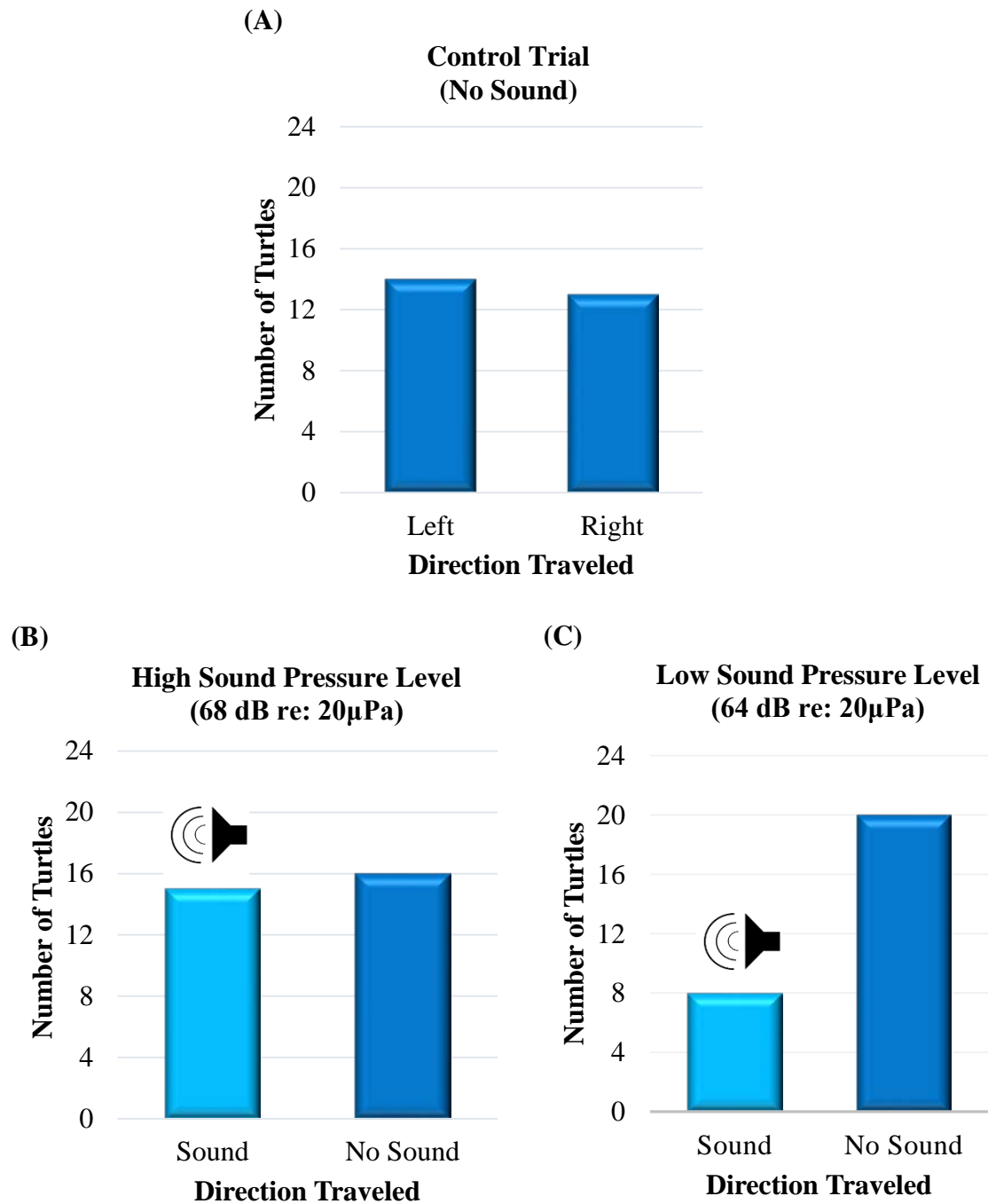**Low Sound Pressure Level
(64 dB re: 20µPa)**

Figure 7. (**A**) Direction of hatchling travel in the presence of no sound. (**B**) Direction of hatchling travel in the high sound pressure trails (68 dB re: 20µPa). (**C**) Direction of hatchling travel in the low sound pressure trails (64 dB re: 20µPa).

Discussion

My results question the potential of hatchlings to use beach wave noise as a seafinding orientation cue. In the presence of the higher sound pressure level, hatchlings exhibited no phonotaxic response; yet, at the reduced sound pressure level hatchlings exhibited a negative phonotaxic response. In control trials, hatchlings oriented to the two sides of the V-maze equally, suggesting the hatchlings in the lower sound pressure group did orient away from the sound.

Although I hypothesized that hatchlings would orient toward the wave noise, being in an unfamiliar environment may have influenced hatchling behavior. While previous studies have not examined the physiological and behavioral responses of sea turtles to sounds in air, or responses to natural sources of environmental sound, several studies examining the impacts of unnatural underwater sounds on turtles have shown notable behavioral responses. In the presence of both explosions and seismic airguns, sea turtles displayed prominent behavioral changes, including erratic swimming and diving behavior, indicating sensitivity to changes in sound pressure (O'Hara and Wilcox 1990, Moein et al. 1994, McCauley et al. 2000, Weir 2007; Hazel et al. 2009; DeRuiter and Doukara 2012).

O'Hara and Wilcox (1990) noted erratic behavior of loggerhead sea turtles in response to seismic airguns, predicted to produce a sound level of 200 dB re: 1µPa at 1 m, used to create a sound barrier at the entrance of a Florida Power and Light water cooling canal. They observed turtles moving away from the airguns and to the surface, or directly below the air gun. Moein et al. (1995) recorded both the behavioral and physiological response of juvenile loggerheads to airguns in a net enclosure in the York River in Virginia. Airguns produced sounds at three frequencies (175, 177, 179 dB) every five seconds for five minutes. During the first exposure to the air gun, the turtles avoided the sound source, but after three exposures the turtles became

habituated to the sound. Moein et al. (1995) also noted increased stress levels amongst the juvenile turtles, however the effects of handling were not taken into account, so stress cannot be attributed to air gun exposure alone. Further, a temporary decrease in hearing was seen in pre- and post-hearing threshold measurements, but a temporary threshold shift (TTS) in hearing sensitivity cannot be determined as hearing was not measured throughout the trials. McCauley et al. (2000) found increased swimming and erratic behavior of one loggerhead and one green sea turtle suspended in an open water cage where they were approached with an air gun. At a received sound pressure level above 166 dB re: 1µPa-rms both turtles exhibited increased swimming. When the pressure level exceeded 175 dB re: 1µPa-rms both turtle became erratic and possibly stressed. DeRuiter and Larbi Doukara (2012) recorded visual observations of loggerhead diving behaviors during seismic air gun surveys off the coast of Angola in the Mediterranean Sea. In response to levels of 252 dB dB re: 1µPa-peak, 57% of turtles dove in response to airgun firing.

The studies outlined above demonstrate the potential for sea turtle behavioral and physiologic responses to sounds played in controlled settings. Just as was noted in the low sound pressure trial of this study, these studies reported the negative phonotaxic response of sea turtles to acoustic signals (O'Hara and Wilcox 1990, Moein et al. 1994, McCauley et al. 2000, Weir 2007, Hazel et al. 2009, DeRuiter and Doukara 2012). However, a rigid analysis cannot be drawn between these studies and this one as I examined the response of hatchlings to natural environmental sounds in air and the sound pressure levels measured in the above studies are significantly higher than the levels in both the high and low sound pressure trial groups. Future studies are needed for continued understanding of sea turtle responses to acoustic stimuli. Specifically, as the findings of behavior and physiologic responses to sound have been limited to

underwater sea turtle responses to unnatural acoustic cues, future studies should begin to examine sea turtle responses to both natural and unnatural sounds in air, as well as natural sounds in water.

A greater understanding of the natural environmental acoustic cues used by sea turtles is needed before the impact of human created sound can be assessed. While conclusive evidence of orientation to wave noise was not found among my hatchlings, the continued rise in anthropogenic beach noise highlights the growing need for research in this area (Ross 1993, McCauley et al. 2000, Andrew et al. 2002, Hildebrand 2009). Many aerial sounds occurring on the beach environment, including vehicle traffic and human conversation, overlap directly with loggerhead hearing (Fig. 8). These sounds have the potential to disorient hatchlings in the process of seafinding as they could mask or cover natural auditory cues. As human actions such as artificial lighting have already been proven to negatively impact hatchlings orientation abilities (Witherington et al. 1990, Kamrowski et al. 2012, Rivas et al. 2015), it is possible that sound can have similar impacts.
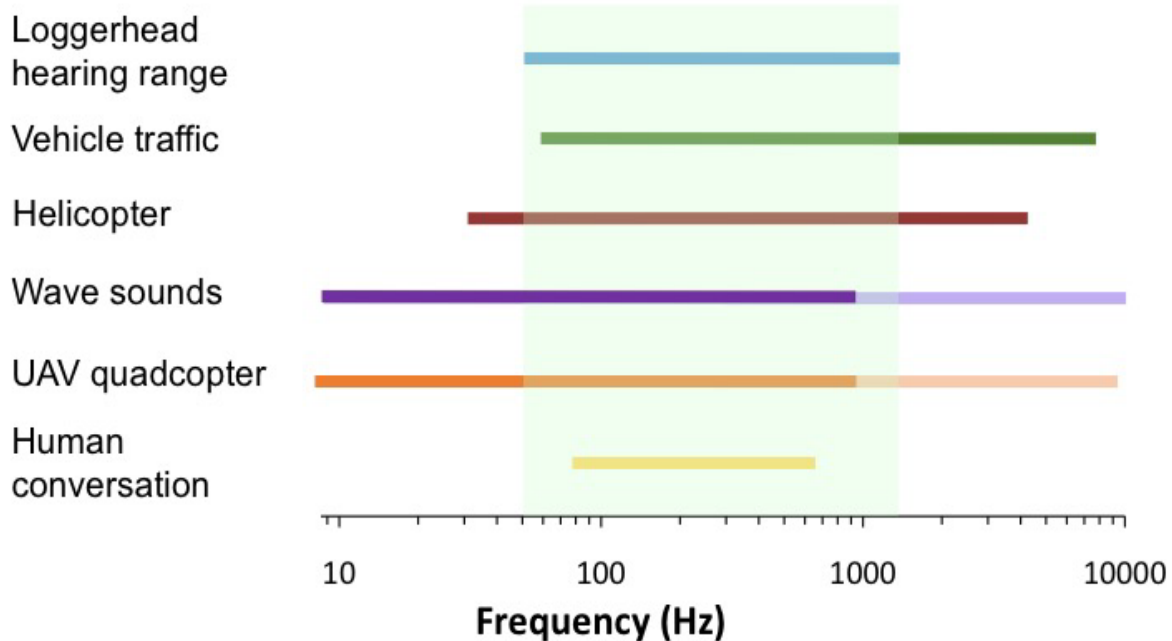
Figure 8. Frequency of aerial sounds (loggerhead hearing range: Piniak unpublished data, vehicle traffic: Can et al. 2006, helicopter: Tatić et al. 2012, wave noise: current study, UAV quadcopter: DJI Phantom 2.0, human conversation: Eulenberg 2011) overlapping with hatchling loggerhead hearing. Overlapping regions are denoted within the green box.

A further explanation for the negative phonotaxic response of hatchlings in the low sound pressure trial may lie in hatchlings use of waves as an orientation cue when moving from the surf zone to deeper offshore waters (Lohmann et al. 1995). Lohmann et al. (1995) found that hatchlings orient in the opposite direction of incoming waves to move in an offshore direction. Using a wave simulator in air, they tested both loggerhead and green sea turtle hatchlings response to wave direction. Turtles tested in response to wave simulations approaching from their left side moved right, while turtles exposed to wave movement from their right turned to the left, indicating that sea turtles can infer the propagation of wave direction through the circular movements that waves create. Though Lohmann et al. (1995) tested wave movement alone, hatchlings may use acoustic cues in combination with wave direction to orient offshore. As

waves have similar acoustic signatures in air and underwater, hatchlings may utilize the sound of crashing waves to orient offshore, resulting in a negative phonotaxic response to this sound both underwater and in air. If this is the case, this would explain the results of the hatchlings in the low sound pressure group, but still does not explain why turtles in the high sound pressure group showed no phonotaxic behavior.

It is also possible that hatchlings were unable to localize sound in the maze. No published studies exist on localization in sea turtles, though the ability has been observed in captivity. Looking at a sub-adult green sea turtle, Norris (2009) conducted behavioral trials where a clicker was played in front of, behind, to the right of, or to the left of the turtle. The turtle's ability to locate the source of the clicker sound was recorded, as well as the time with which the trail lasted. After six weeks, with two trials per day, the turtle was able to successfully identify the sound source in more trails than those in which it failed to locate the sound. This study focused on a rescued turtle residing at the Mote Marine Laboratory who originally presented following extensive fractures to the sides and top of its skull. It cannot be ruled out that these injuries did not impact the sensory abilities of this turtle. Further, the study did not report the frequency of the clicker sound played, which hinders comparisons to the range and peak sensitivity of green sea turtle hearing. While these results show the potential for auditory localization in sea turtles, they do not offer conclusive results. Moreover, localization in sub-adult sea turtles do not confirm the ability in hatchlings due to the anatomical size differences between the skulls of hatchling and older turtles, specifically in relation to distance between the ears.

Published evidence of localization in comparable turtle species is presented by Lenhardt (1981). Looking at the semiaquatic turtle, *Chrysemys scripta*, and the terrestrial turtle, *Terrapene carolina major*, Lenhardt observed behavioral patterns indicative of sound localization. The

turtles in this study displayed head scanning, as well as retreating and advancing behaviors over a 30 to 90-minute period before making a decision as to where the sound was located. The turtles in my study, on the other hand, chose a side of the maze in under 5 minutes, indicating very little time was allocated toward deciding which side of the maze to move down. As my study was conducted in a light-tight V-maze I cannot conclusively say if the hatchlings exhibited any head scanning or advancing and retreating behaviors indicative of sound localization. Future studies should consider the use of a camera to observe hatchling behavior as they orient within the maze.

My results may have been influenced by the design of and sound field within the V-maze. A general pattern of decreasing sound pressure level with distance from the speaker was noted, yet several points within the maze registered higher levels than expected. Most notably, the highest sound pressure level in both trail groups was recorded at the hatchling start location rather than directly in front of the speaker. Although sound-reducing foam was applied to the entire outer cover of the V-maze, reflection of sound within the maze or in the larger room may account for this unexplained pattern in the sound field. Future studies may consider using a circular arena, or larger V-maze to create a larger difference in the sound pressure level between the two sides of the maze.

The results of my study indicate the need for further auditory orientation experiments to better understand hatchling behavioral responses to environmental acoustic cues. As anthropogenic sound sources continue to increase in frequency and intensity, it remains critical to better understand how sea turtles utilize acoustic cues in order to address the possible impacts of anthropogenic noise. A better understanding of the biological significance of acoustic cues for sea turtles can lead to the creation of more effective conservation and management plans.

Literature Cited

Aguirre, A. A., and P. L. Lutz. 2004. Marine turtles as sentinels of ecosystem health: is fibropapillomatosis an indicator?. *Ecohealth* 1: 275-283.

Andrew, R. K., B. M. Howe and J. A. Mercer. 2002. Ocean ambient sound: comparing the 1960s with the 1990s for a receiver off the California coast. Acoustic Research Letters Online 3(2): 65-70 aaw

Avens, L., and K. J. Lohmann. 2003. Use of multiple orientation cues by juvenile loggerhead sea turtles *Caretta caretta*. Journal of Experimental Biology 206: 4317-4325.

Au W. W. L., and M. C. Hastings. 2008. Principles of Marine Bioacoustics. Series: Modern acoustics and signal processing. Springer, New York, New York, USA.

Bartol, S. M., J. A. Musick and M. L. Lenhardt. 1999. Auditory evoked potentials of the loggerhead sea turtle (*Caretta caretta*). Copeia 3: 836-840.

Bartol, S. M., and Ketten, D. R. 2006. Turtle and tuna hearing. Pages 98-103 *in* Y. Swimmer and R. Brill, editors. Sea Turtle and Pelagic Fish Sensory Biology: Developing Techniques to Reduce Sea Turtle Bycatch in Longline Fisheries. NOAA Technical Memorandum NMFS-PIFSC-7. Honolulu, Hawaii, USA.

Bolten, A. L., and B. E. Witherington. 2003. Loggerhead sea turtles. Smithsonian Books, Washington, D.C., USA.

Can, A., Leclercq, L., Lelong, J., and Bottledooren, D. 2010. Traffic noise species spectrum analysis: dynamic modeling vs. experimental observations. Applied Accoustics 17.8: 764-770.

Carr, A., and L. Ogren. 1960. The ecology and migrations of sea turtles, 4: the green turtle in the Caribbean Sea. Bulletin of the AmericanMuseum of Natural History 121*: 7–48.

Casale, P. and Tucker, A.D. 2015. *Caretta caretta*. The IUCN Red List of Threatened Species 2015: e.T3897A83157651. http://dx.doi.org/10.2305/IUCN.UK.2015 4.RLTS.T3897A83157651.en. Accessed April 16, 2016.

Chasek, P. S., J. W. Brown, and D. L. Downie. 2014. Global environmental politics. Sixth edition. Westview Press, Philadelphia, Pennsylvania, USA.

Crognale, M. A., S. A. Eckert, D. H. Levenson and C. A. Harms. 2008. Leatherback sea turtle Dermochelys coriacea visual capacities and potential reduction of bycatch by pelagic longline fisheries. Endangered Species Research 5: 249-256.

DeRuitter S. L., and K. L. Doukara. 2012 Loggerhead turtles dive in response to airgun sound exposure. Endangered Species Research 16: 55-63.

Endres, C. S., and K. J. Lohmann. 2012. Perception of dimethyl sulfide (DMS) by loggerhead sea turtles: a possible mechanism for locating high-productivity oceanic regions for foraging. Journal of Experimental Biology 215: 3535-3538.

Eulenberg, J. 2011. Fundamental frequency and the glottal pulse. Michigan State University. East Lansing, Michigan, USA. https://msu.edu/course/asc/232/study_guides/F0_and_ Glottal_Pulse_Period.html. Accessed February 22, 2016.

Fuxjager, M. J., B. S. Eastwood and K. J. Lohmann. 2011. Orientation of hatchling loggerhead sea turtles to regional magnetic fields along a transoceanic migratory pathway. Journal of Experimental Biology. 214: 2504-2508.

Gless, J. M., Salmon, M., and Wyneken, J. 2008. Behavioral responses of juvenile leatherbacks *Dermochelys coriacea* to lights used in the longline fishery. Endangered Species Research 5: 239-247.

Grassman M., and D. W. Owens. 1987. Chemosensory imprinting in juvenile green sea turtles, *Chelonia mydas*. Animal Behavior 35: 929-931.

Hamilton, L., and T. G. Safford. 2015. Environmental views from the coast: public concern about local to global marine issues. Society & Natural Resources 28(1): 57-74.

Hazel, J., I. R. Lawler, H. Marsh and S. Robson. 2007. Vessel speed increases the collision risk for the green turtle *Chelonia mydas*. Endangered Species Research 3: 105-113.

Hildebrand, J. A. 2009. Anthropogenic and natural sources of noise in the ocean. Marine Ecology Progress Series 395: 5-20.

Howard, J., and R. B. Griffis. 2013. Oceans and marine resources in a changing climate: a technical input to the 2013 national climate assessment. Island Press, Washington, D.C., USA.

Kamrowski, R. L., Limpus, C., Moloney, J., and Hamann, M. 2012. Endangered Species Research 19: 85-98.

Lanyon, J. M., C. J. Limpus, and H. Marsh. 1989. Dugongs and turtles - grazers in the seagrass system. Pages 610-634 *in* A. W. D. Larkum, A. J. McComb and S. A. Shepherd, editors. Biology of seagrasses. Elsevier Science Limited, New York, New York, USA.

Lavender, A. L., Bartol, S. M., and Bartol, I. K. 2014. Ontogenetic investigation of underwater hearing capabilities in loggerhead sea turtles (Caretta caretta) using a dual testing approach. Journal of Experimental Biology 217: 2580-2589.

Lenhardt, M. L. 1981. Evidence for auditory localization ability in the turtle. Journal of Auditory Research 21:255-261.

Lenhardt, M. L., Klinger, R. C., and Musick, J. A. 1985. Marine turtle middle-ear anatomy. Journal of Auditory Research 25: 66-72.

Lohmann, K. J., Swartz, A. W., Lohmann, C. M. 1995. Perception of ocean wave direction by sea turtles. Journal of Experimental Biology 198:1079-1085.

Lohmann, K. J., S. D. Cain, S. A. Dodge and C. M. F. Lohmann. 2001. Regional magnetic fields as navigational markers for sea turtles. Science 294: 364-366.

Lohmann, K. J., C. M. F. Lohmann, L. M. Ehrhart, D. A. Bagley and T. Swing. 2004. Geomagnetic map used in sea turtle navigation. Nature 428: 909-910.

Lohmann, K. J., Wang, J. H., Boles, L. C., McAlister, J., and Lohmann, C. M. F. 2006. Development of turtle-safe light sticks for use in longline fisheries. Pages 65-76 *in* Swimmer, Y. and Brill, R., editors. Sea turtle and pelagic fish sensory biology: Developing techniques to reduce sea turtle bycatch in longline fisheries. Pacific Island Fisheries Service Center, Honolulu, Hawaii, USA.

Lutz, P. L., and J. A., Musick. 1997. The biology of sea turtles. CRC Press, Boca Raton, Florida, USA.

Magyar, T. 2008. The impact of artificial lights and anthropogenic noise on Loggerheads (Caretta caretta) and Green Turtles (Chelonia mydas), assessed at index nesting beaches in Turkey and Mexico. Dissertation. University of Bonn, Bonn, Germany.

Manton, M., A. Karr and D. W. Ehrenfeld. 1972. Chemoreception in the migratory sea turtle, *Chelonia mydas*. Biological Bulletin 143: 184-195.

Martin K. J., S. C. Alessi, J. C. Gaspard, A. D. Tucker, G. B. Bauer and D. A. Mann. 2012. Underwater hearing in the loggerhead sea turtles (*Caretta caretta*): a comparison of behavioural and auditory evoked potential audiograms. Journal of Experimental Biology 215: 3001-3009.

McCauley, R. D., J. Fewtrell, A. J. Duncan, C. Jenner, M-N. Jenner, J. D. Penrose, R. I. T. Prince, A. Adhitya, J. Murdoch and K. McCabe. 2000. Marine seismic surveys – A study of environmental implications. APPEA Journal: 692-708.

McFarlane, R. W. 1963. Disorientation of loggerhead hatchlings by artificial road lighting. Copeia: 153.

Moein, S. E., Musick, J. A., Keinath, J. A., Barnard, D. E., and George, R. 1994. Evaluation of seismic sources for repelling sea turtles from hopper dredges. The Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia, USA.

Mrosovsky, N., and S. J. Shettleworth. 1968. Wavelength preferences and brightness cues in the water finding behavior of sea turtles. Behaviour 32: 211–257.

National Marine Fisheries Service. 2008. Southeast Fisheries Science Center Sea Turtle
    Research Techniques Manual. NOAA Technical Memorandum NMFS-SEFSC-579: 92.

NOAA Fisheries. 2014. Loggerhead turtle (Caretta caretta).
    http://www.nmfs.noaa.gov/pr/species/turtles/loggerhead.htm. Accessed April 14, 2016.

Norris, R. 2009. Sound source localization in Chelonia mydas. Xavier University, Cincinnati,
    Ohio, USA.

O'Hara, J., and J. R. Wilcox. 1990. Avoidance responses of loggerhead turtles, *Caretta caretta*,
    to low frequency sound. Copeia 2: 564-567.

Owens, D. W., M. A. Grassman and J. R. Hendrickson. 1982. The imprinting hypothesis and sea
    turtle reproduction. Herpetologica 38: 124-135.

Piniak, W. E. D. 2012. Acoustic ecology of sea turtles: implications for conservation.
    Dissertation. Duke University, Durham, North Carolina, USA.

Philibosian, R. 1976. Disorientation of Hawksbill turtle hatchlings, Eretmochelys imbricata, by
    stadium lights. Copeia 4: 81.

Richardson, J. W., Greene, Jr., C. R., Malme, C. I., and Thomson, D. H. 1995. Marine Mammals
    and Noise. Academic Press, San Diego, California, USA.

Ridgway, S. H., E. G. Wever, J. G. McCormick, J. Palin and J. H. Anderson. 1969. Hearing in
    the giant sea turtle, *Chelonia mydas*. Proceedings of the National Academy of Science
    USA 64: 884-890.

Rivas, M. L., Tomillo, P. S., Uribeondo, J. D., and Marco, A. 2015. Leatherback hatchling sea
    finding in response to artificial lighting: interaction between wavelength and moonlight.
    Journal of Experimental Marine Biology and Ecology 463: 143-149.

Ross, D. 1993. On underwater ambient noise. Institute of Acoustics Bulletin18: 5-8.

Salmon, M., and J., Wyneken. 1994. Orientation by hatchling sea turtles: mechanisms and
    implications. Herpetological Natural History 2: 13-26.

Schlacher, T.A., J. D. Dugan, D. S. Schoeman, M. Lastra, A. Jones, F. Scapini, A. McLachlan,
    and O.Defeo. 2007. Sandy beaches at the brink. Diversity and Distributions 13(5): 556-
    560.

Swimmer, Y. and Brill, R. 2006. Sea turtle and pelagic fish sensory biology: Developing
    techniques to reduce sea turtle bycatch in longline fisheries. Pacific Island Fisheries
    Service Center, Honolulu, Hawaii, USA.

Swimmer, Y. and Wang, J. H. 2007. 2006 Sea turtle and pelagic fish sensory physiology workshop, September 12-13, 2006. NOAA Technical Memorandum NMFS-PIFSC-12. Pacific Island Fisheries Service Center, Honolulu, Hawaii, USA.

Tatić, B., Bogojević, N., Todosijević, S., Šoškić, Z. 2012. Analysis of noise level generated by helicopters with various numbers of blades in the main rotor. Niš 17-19.10: 249-253.

Wang, J. H., Boles, L. C., Higgins, B., and Lohmann, K. J. 2007. Behavioral responses of sea turtles to lightsticks used in longline fisheries. Animal Conservation 10: 176-182.

Wang, J. H., L. C. Boles, B. Higgins and K. J. Lohmann. 2007. Behavioral responses of sea turtles to lightsticks used in longline fisheries. Animal Conservation 10: 176-182.

Wang, J. H., S. Fisler and Y. Swimmer. 2010. Developing visual deterrents to reduce sea turtle bycatch in gill nets. Marine Ecology Progress Series 408: 241-250.

Weir, C. R. 2007. Observation of marine turtles in relation to seismic airgun sound off Angola. Marine Turtle Newsletter 116: 17-20.

Wever, E. G. and Vernon, J. A. 1956. The sensitivity of the turtle's ear as shown by its electrical potentials. Proceedings of the National Academy of Sciences of the United States 42: 213-220.

Wever, E. G. 1978. The reptile ear. Princeton University Press, Princeton, New Jersey, USA.

Witherington, B. E., Bjorndal, K. A., and McCabe, C. M. 1990. Temporal pattern of nocturnal emergence of loggerhead turtle hatchlings from natural nests. Copeia 1990 (4): 1165 1168.

Witherington, B.E., and Bjorndal, K. A. 1991. Influences of wavelength and intensity of hatchling sea turtles phototaxis: Implications for sea-finding behavior. Copeia 4: 1060 1069

Yost, W. A. 2007. Fundamentals of Hearing: An Introduction. Fifth Edition. Elsevier Press (Academic). New York, New York, USA.

Young, M., M. Salmon, and R. Forward. 2012. Visual wavelength discrimination by the loggerhead turtle, Caretta caretta. Biological Bulletin. 222: 46-55.