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Acoustic deterrence of bighead carp (*Hypophthalmichthys nobilis*) to a broadband sound stimulus

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ABSTRACT

Recent studies have shown the potential of acoustic deterrents against invasive silver carp (*Hypophthalmichthys molitrix*). This study examined the phonotaxic response of the bighead carp (*H. nobilis*) to pure tones (500–2000 Hz) and playbacks of broadband sound from an underwater recording of a 100 hp outboard motor (0.06–10 kHz) in an outdoor concrete pond (10 × 5 × 1.2 m) at the U.S. Geological Survey Upper Midwest Environmental Science Center in La Crosse, WI. The number of consecutive times the fish reacted to sound from alternating locations at each end of the pond was assessed. Bighead carp were relatively indifferent to the pure tones with median consecutive responses ranging from 0 to 2 reactions away from the sound source. However, fish consistently exhibited significantly ($P < 0.001$) greater negative phonotaxis to the broadband sound (outboard motor recording) with an overall median response of 20 consecutive reactions during the 10 min trials. In over 50% of broadband sound tests, carp were still reacting to the stimulus at the end of the trial, implying that fish were not habituating to the sound. This study suggests that broadband sound may be an effective deterrent to bighead carp and provides a basis for conducting studies with wild fish.

Introduction

The bighead carp (*Hypophthalmichthys nobilis*) is an invasive fish species in North America and has established breeding populations in the Mississippi River Watershed. Range expansion of these fish into the Great Lakes is a concern because they are present in the northern regions of the Illinois River (Kolar et al., 2007; Sass et al., 2010) and have been found in the Chicago Sanitary and Ship Canal (Moy et al., 2011) near Lake Michigan. These fish, along with the closely related silver carp (*H. molitrix*), evolved in Asia and were intentionally brought to the United States for use in wastewater treatment plants and aquaculture facilities (Kelly et al., 2011; Kolar et al., 2007). Both species are an ecological concern because they compete with native species, such as paddlefish (*Polyodon spathula*; Schrank et al., 2003), gizzard shad (*Dorosoma cepedianum*; Sampson et al., 2009), and bigmouth buffalo (*Ictiobus cyprinellus*; Irons et al., 2007), for food and space. While adults from both *Hypophthalmichthys* species can grow up to 40–50 kg, they are planktivores, which precludes them from being caught via angling or baited traps. Furthermore, these filter feeders will consume both zooplankton and phytoplankton and could alter the entire food web in rivers where they are abundant (Sass et al., 2014).

As part of an integrated pest management strategy, state and federal agencies throughout the Midwest are prioritizing the development of effective non-physical deterrents, including acoustic barriers, to prevent further bighead and silver carp range expansion. Acoustic deterrents, often in combination with other techniques such as bubbles or strobe lights, have been moderately successful at dam and power plant intakes (see Noatch and Suski, 2012 for a review). Barriers utilizing ultrasound (122–128 kHz; Ross et al., 1993) or varied low-frequency sound (20–600 Hz; Maes et al., 2004) successfully repelled 87% and 60% of clupeids, respectively. There is evidence that bighead carp are deterred by sound (20–2000 Hz) combined with bubbles in studies conducted on both captive (Pegg and Chick, 2004; Taylor et al., 2005) and wild fish (Ruebush et al., 2012). However, an investigation into the phonotaxic response of invasive carp to sound alone is important for the evaluation of acoustic deterrents.

Bighead carp are ostariophysans and possess Weberian ossicles, which connect the gas bladder to the inner ear (Fay and Popper, 1999), allowing for higher frequency hearing than many non-ostariophysan species. Lovell et al. (2006) indicated bighead carp frequency sensitivity up to 3 kHz. However, as the researchers did not test above 3 kHz, it is uncertain if bighead carp can hear beyond this frequency. Ladich (1999) studied species from four ostariophysan orders (Cypriniformes, Characiformes, Siluriformes, and Gymnotiformes) and elicited auditory brainstem responses up to at least 5 kHz in all species. Furthermore, brown bullhead (10–13 kHz; *Ameiurus nebulosus*;

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Poggendorf, 1952) and neotropical catfish (6 kHz; *Lophiobagrus cyclurus*; Lechner et al., 2011) have frequency sensitivity beyond 5 kHz. Therefore, it is possible that bighead carp can detect higher frequencies than those previously reported by Lovell et al. (2006).

The silver carp is notorious for its jumping behavior, which can be elicited when motorized watercraft move through carp-infested areas. Playbacks of the broadband (0.06–10 kHz) sound emitted by outboard motors caused wild silver carp to jump (Mensinger, unpublished) and elicited negative phonotaxis in captive fish (Vetter et al., 2015), however bighead carp do not jump (Kolar et al., 2007). Therefore, the effect of similar acoustic stimulation on bighead carp is unknown, as their underwater behavior is difficult to monitor in turbid water. Since silver and bighead carp coexist and will hybridize, if bighead carp are affected similarly by sound, the two species could be co-managed by acoustic deterrents.

The goal of this study was to examine the behavioral response of bighead carp to pure tones and broadband sound stimuli, which was successful in modulating silver carp swimming behavior. It was predicted that bighead carp would also demonstrate negative phonotaxis to broadband sound, providing further support for the development of acoustic barriers to manage these species.

Methods

Animal husbandry

All experiments were conducted at the U.S. Geological Survey (USGS) Upper Midwest Environmental Sciences Center (UMESC) in La Crosse, Wisconsin. Bighead carp ($n = 50$; total length: 212 ± 7.7 mm; wet weight: 101.4 ± 12.3 g; mean ± standard deviation) were obtained in the summer of 2013 from Osage Catfisheries, a private aquaculture farm in Osage Beach, Missouri, USA. Fish were maintained in 1500 L flow-through indoor ponds and fed trout starter diet (Skretting, Tooele, UT) at a rate of 0.5% body weight per day (Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government). A Chapter NR 40 Permit for Possession, Transport, Transfer, or Introduction of Prohibited or Restricted Species was obtained from the Wisconsin Department of Natural Resources prior to acquisition of test animals and movement to outdoor ponds and experiments were conducted under UMESC Animal Care and Use Committee Protocol Number AEH-12-PPTAC-01.

Behavioral experiments

Behavioral experiments were conducted in an above ground $10 \times 5 \times 1.2$ m (60 kL) outdoor concrete flow-through pond. Each group ($N = 5$) of ten naïve fish was allowed to acclimate in the outdoor pond for at least 48 h prior to the initiation of experiments. Five two-day trials were conducted from June through August 2014. At the conclusion of each trial, the pond was drained, refilled, and naïve fish ($N = 10$) added.

Sound stimuli

Sound was delivered via one of two pairs of underwater speakers (UW-30, Lubell Labs Inc., Whitehall, OH) that were placed 1.0 m from each end of the pond, 1.6 m from the nearest side-wall, 1.8 m apart, and positioned so that sound was projected along the longitudinal axis of the pond (Fig. 1). Acoustic stimuli consisted of pure tones (500, 1000, 1500, or 2000 Hz), generated by Audacity 2.0.5 software, and broadband sound, recorded underwater from an outboard motor (100 Hp 4-stroke, Yamaha, Kennesaw, GA). The outboard motor sound was recorded with a hydrophone (HTI-96-MIN, High Tech Inc., Long Beach, MS), in the Illinois River near Havana, Illinois, USA (40° 17′ 30″ N, 90° 04′ 20″ W). Sound was recorded in approximately 1 m of water while the boat transited past the hydrophone at 32 km/h at a nearest distance of 10 m.

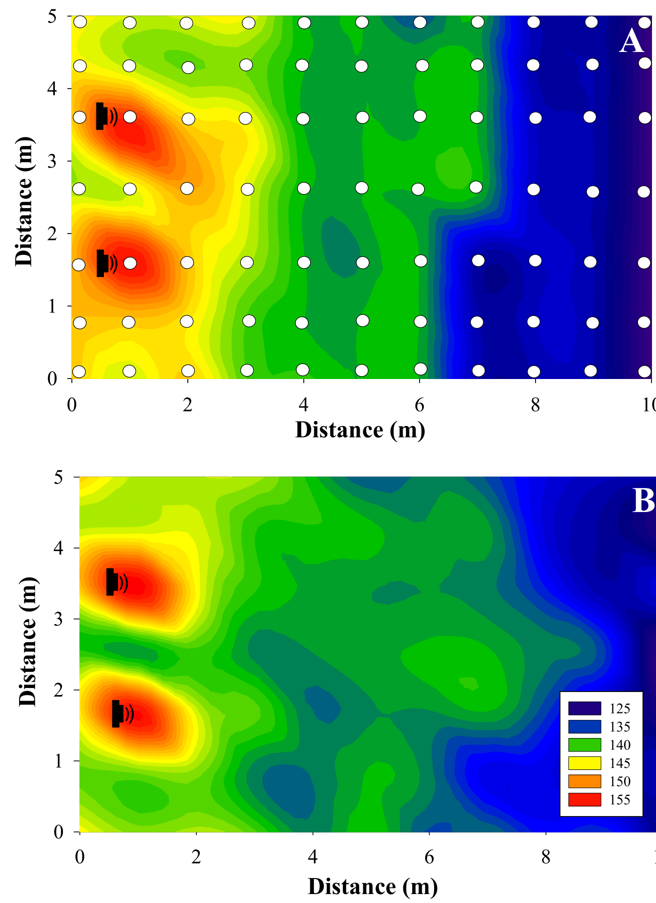

Fig. 1. Sound pressure level in the experimental pond. The sound intensity was measured using a hydrophone at a depth of 0.6 m at 77 intervals throughout the pond during broadband sound playback. The speakers and points of measurement (white circles in upper figure) are indicated. The colors represent the sound intensity level (dB re 1 μPa), indicated in the scale on the lower right. A) 1000 Hz pure tone; B) Broadband sound stimulus.

The sound was amplified with a UMA-752 amplifier (UMA-752, Peavey Electronics, Meridian, MS) and each speaker pair was controlled manually with a switchbox (MCM Electronics, Centerville, OH). Each pond contained a single hydrophone to monitor the sound stimuli, which were recorded using a PowerLab 4SP data acquisition system and LabChart 7 software (AD Instruments, Colorado Springs, CO). To map the acoustic field, recordings of the broadband sound and 1000 Hz pure tone were made at 77 positions throughout the tank at a depth of 0.6 m which was the depth at which fish were most often swimming. Sound pressure levels were approximately 155 dB re 1 μPa directly in front of the speakers for both pure tones and broadband sound and dropped below 120 dB re 1 μPa at the far end of the pond (Fig. 1). All pure tone stimuli showed a narrow energy peak at the dominant frequency (Fig. 2). The broadband sound produced a spectrum of sound from 0.06–10 kHz, with maximal energy contained in two peaks from 0.06–2 kHz and 6–10 kHz (Fig. 2).

Behavior was monitored with eight overhead SONY bullet 500 TVL video cameras connected to ProGold software (Security Camera World, Cooper City, FL). The cameras continuously monitored the fish during daylight hours on testing days and provided full coverage of the pond. The water remained clear throughout the entire study and fish were visible in all areas of the pond. All monitoring equipment (i.e. cameras, speaker switchbox, etc.) was contained within a shelter located approximately 50 m from the test pond, therefore eliminating any experimenter influence on fish behavior. Additionally, hydrophone

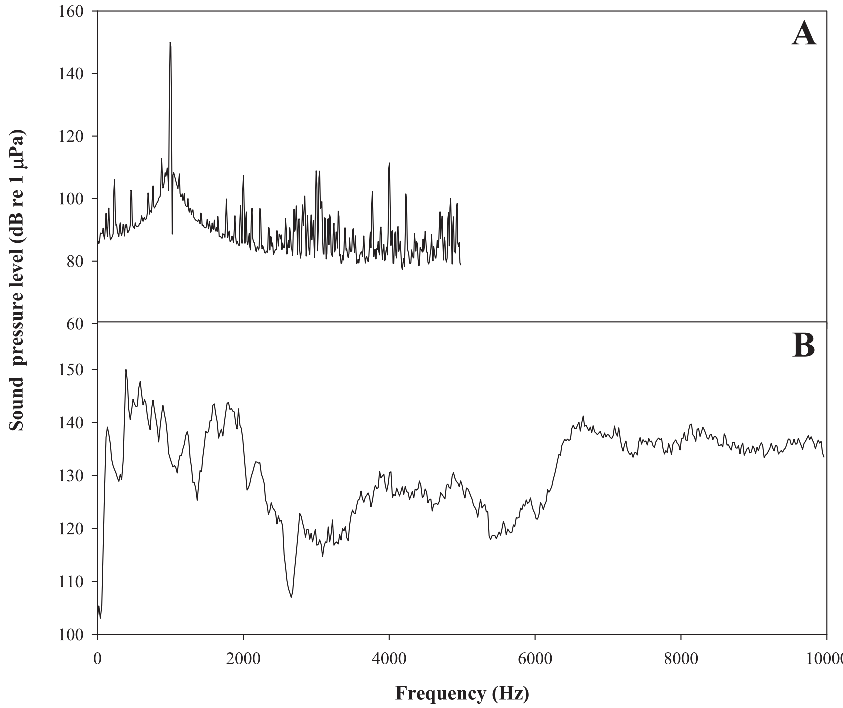

Fig. 2. The power spectrum of the A) pure tone (1000 Hz) and B) broadband sound is plotted versus frequency from a hydrophone a depth of 0.6 m directly in front of the speaker (<1 m) during sound playback in the pond (Modified from Vetter et al., 2015).

records were examined for sound artifacts during speaker onset and offset, and only the sound stimuli were detected.

The bighead carp demonstrated schooling behavior, consistently staying in the middle of the water column; therefore the fish in each trial were treated as a single unit, with position determined as the approximate center of the school. An "end zone" was established at each end of the pond and was defined as the area of the pond within 2.5 m of the end wall. The order of stimuli presentation (pure tones vs. broadband sound) was determined randomly before each trial. Four broadband and 12–16 pure tone sound trials (3–4 trials for each 500, 1000, 1500, and 2000 Hz pure tone) were conducted on each group. Experimental trials were initiated by playing a 30 s sound stimulus from the speaker pair in the end zone occupied by the fish. If the fish swam away from the sound and crossed the centerline of the pond within 30 s, then the sound source was switched to the opposite end of the pond when the fish reached the far end zone. This procedure was immediately repeated, and the sound stimulus replayed, until the fish stopped responding to the sound or 10 min elapsed. Consecutive responses were defined as fish reacting to two or more sound presentations from opposite ends of the pond. If the fish did not cross the centerline within 30 s, remained in the same location, or swam towards the sound, then this behavior was scored as no response and the stimulus was not played from the opposite speaker pair. PowerLab recordings were time synchronized with video recording, to compare the onset of sound with the carp's behavioral response. Furthermore, when alternating the sound source, the active speakers were turned off before the opposite speaker pair was powered on, leaving approximately a 1 s sound gap when speakers were switched during sound playback.

Pure tone trials

Fish position was monitored for 10 min prior to the acoustic stimulus. Each trial began with a 30 s pure tone (500, 1000, 1500, or 2000 Hz) initiated from the speaker pair in the end zone containing the fish. If the fish responded to the initial stimulus, the sound source was alternated to the other end of the pond as many times as was necessary, until the fish no longer responded. After the fish failed to respond to either the initial or subsequent stimuli, they were allowed a recovery time of 90 to 180 s before the next 30 s presentation of the same frequency. This was repeated two more times during each frequency trial. At the end of every pure tone trial, a 30 s clip of the broadband sound was played. If the fish responded to the sound during this 30 s broadband sound clip, the sound source was alternated in the same method as was employed when exposing fish to the pure tones. Fish were allowed at least 15 min of recovery after each pure tone trial.

Broadband trials

Broadband sound trials were conducted following a similar method to the pure tones. Because the fish were more responsive to the broadband sound, the protocol was modified slightly and the 30 s outboard motor recording was looped continuously (except for the approximate 1 s delay when one speaker pair was turned off and the opposite pair turned on), with only the speaker position changing. The sound stimulus was switched to the opposite speaker pair as soon as the school crossed into the opposite end zone. Each broadband sound trial was terminated after the fish no longer responded to the stimulus or 10 min elapsed. Fish were allowed at least 30 min to recover after each broadband sound trial.

Data analysis

Fish position was monitored during the 10 min before (control) and through the application of the sound stimulus for every trial by recording the position in meters (x, y) of the midpoint of the school every 5 s. Swim speed was quantified for experimental fish that reacted to the sound using frame by frame analysis of the video recording (30 frames per second). The elapsed time from when the fish turned and swam 2.0 m away from the sound stimulus was calculated and the swim speed determined. The swim speeds were only assessed for fish that reacted to the sound stimulus and swam 2.0 m in <30 s. Fish that took longer than 30 s or did not respond, were excluded from analysis, which included 68.3% of 500 Hz, 61.5% of 1000 Hz, 30.0% of the 1500 Hz, 48.4% of 2000 Hz, and 0% of broadband trials. For controls, fish were observed for a 10 min period of continuous swimming in the absence of sound, and the time it took the school to transverse

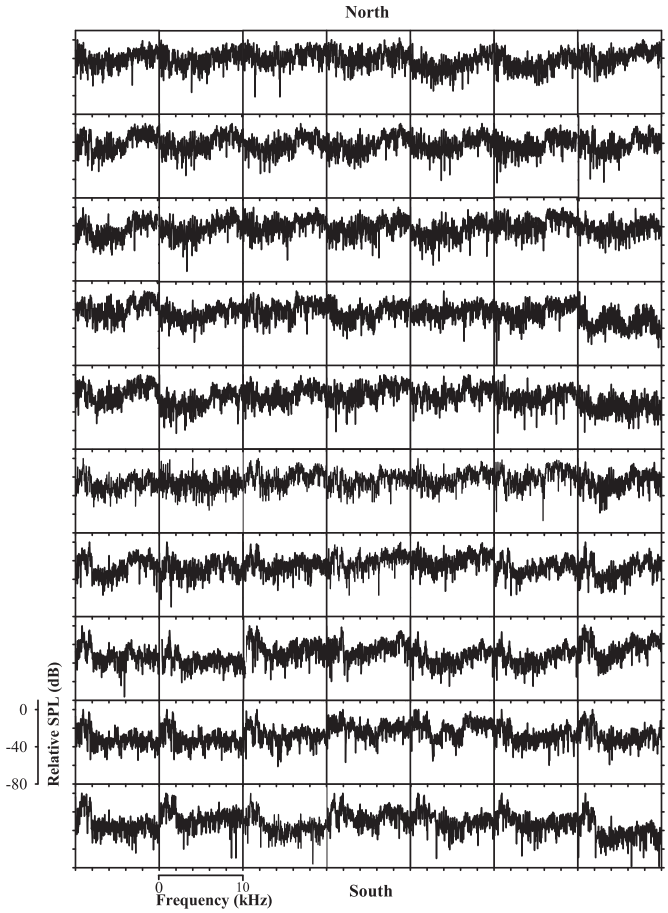

Fig. 3. The power spectrum from measurement locations in the pond is plotted versus frequency during playback of the broadband sound. The maximum sound pressure level at each location was assigned a decibel level of 0 and each spectrum is plotted relative to the maximum sound pressure level at each location.

2 m intervals was determined (15.6% of the time, fish exceeded 30 s to swim 2 m and these values were not included). Control speeds were determined prior to testing or at least an hour after the last exposure to sound stimuli.

All statistical tests were performed with SigmaPlot for Windows (version 12.5). Shapiro-Wilk tests indicated that the response number and swimming speeds data were not normally distributed ($P < 0.05$) and therefore a non-parametric Kruskal-Wallis ANOVA with a Dunn's post hoc test was used. The median along with the upper and lower quartiles for the response numbers and swimming speed are reported using the following format: (median; 1st Q, 3rd Q) or median (1st Q, 3rd Q).

Results

The sound recorded within 1 m of the front of the speaker showed that for the pure tones, most of the energy was centered at the dominant frequency, while the broadband sound ranged from 0.06–10 kHz, with the highest energy contained in frequencies <2 kHz (Fig. 2). Sound pressure levels peaked in front of and behind the speakers and the end zone nearest the active speakers contained the areas of highest sound pressure levels, with sound attenuating as it traveled towards the far end of the pond (Fig. 1). Fig. 3 illustrates the power spectrum for the broadband sound throughout the pond.

Swimming behavior

Figs. 4 and 5 show the swimming behavior from one representative school of bighead carp from control and experimental trials. During the control trials, the fish primarily moved around the perimeter at a relatively consistent speed, with the school shown completing approximately 5.5 circuits of the pond over the 10 min observation period (Fig. 4A). In contrast, the fish responding to the broadband sound favored the longitudinal center of the tank when moving away from the sound source (Fig. 4B). The school showed no response to the 500, 1000, or 2000 Hz pure tones, as the fish either remained in the area or swam towards the stimulus (Fig. 5). For the 1500 Hz tone, fish reacted once to the first playback and twice to the third, but then stopped responding and remained in the same area even though the sound was present (Fig. 5). However, at the end of every pure tone trial, the

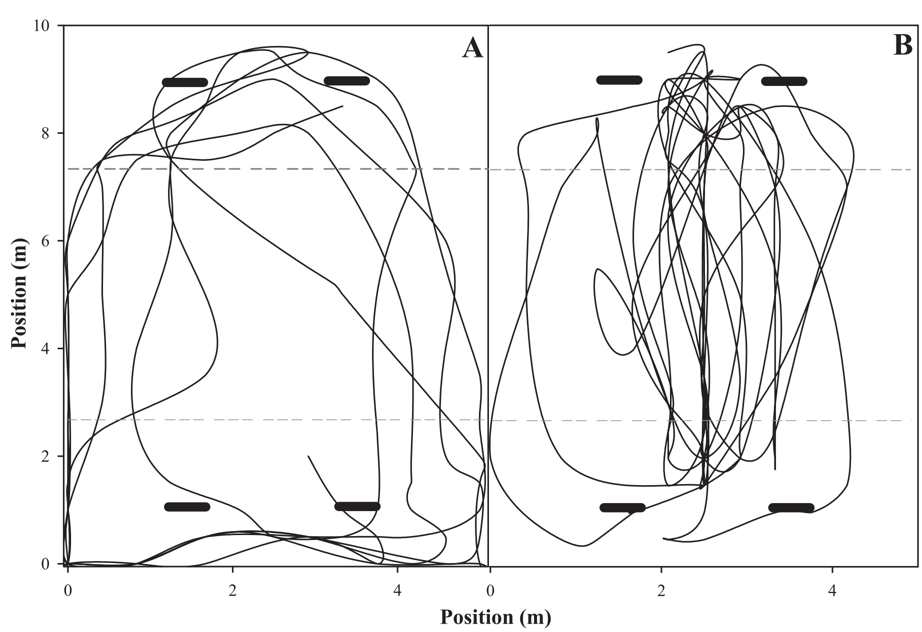

Fig. 4. Bighead carp swimming behavior. The solid black lines represent the speaker location and the dotted line represents the “end zones.” The traces mark the horizontal and longitudinal position (m) of the center of one representative school of bighead carp during a control and broadband sound trial, with the fish position mapped every 5 s. A) Control; B) Broadband sound.

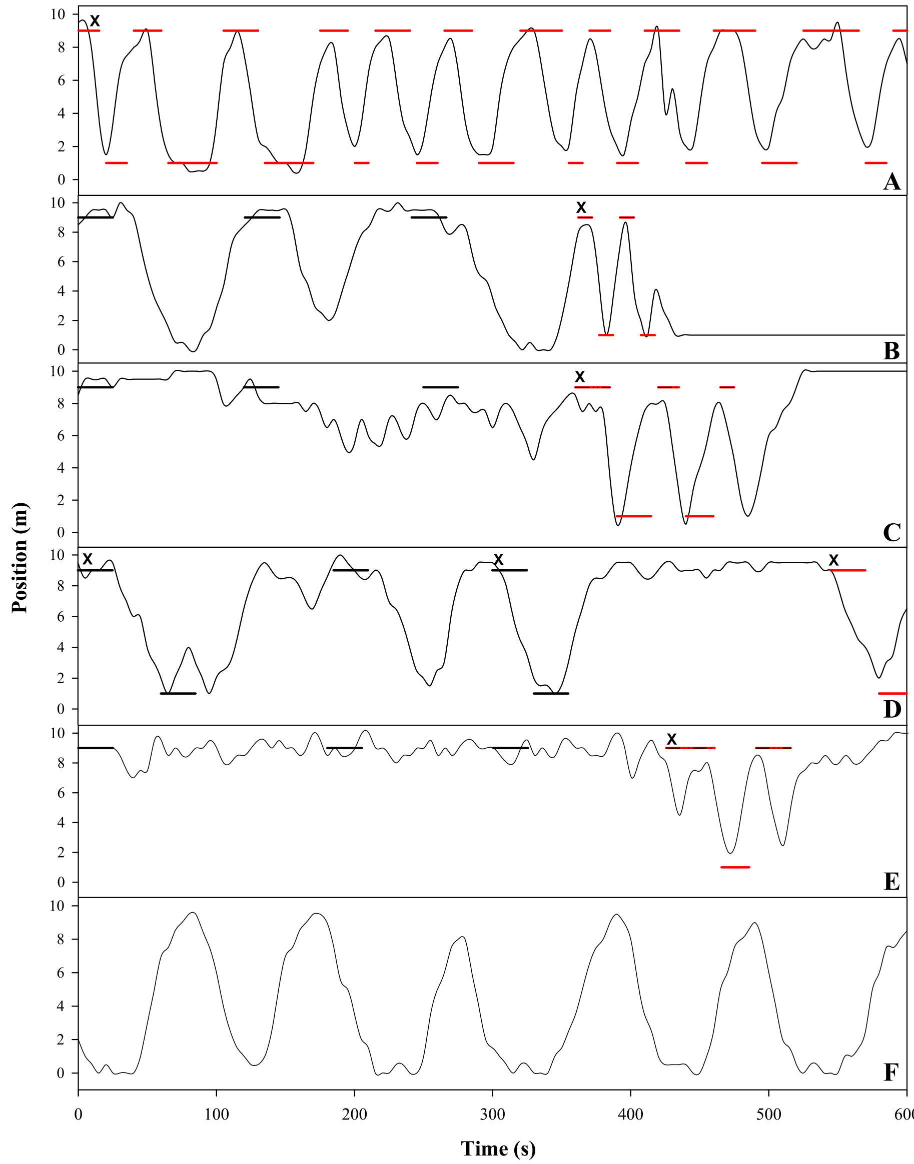

Fig. 5. Representative bighead carp behavioral response to acoustic stimulation for one school. The longitudinal position (m) of the center of the school is plotted versus time (s) with fish position mapped every 5 s. Solid lines above and below each fish position trace indicate the location and duration of the sound stimulus (black = pure tone; red = broadband sound). The X represents the first negative phonotaxis of a series or resumption after non-responsive trials. For clarity, successive responses in a series are not labeled. A) Broadband sound; B) 500 Hz; C) 1000 Hz; D) 1500 Hz; E) 2000 Hz; F) Control (no sound).

fish responded at least once to the broadband sound stimulus. The same school responded to the broadband sound stimulus 23 consecutive times over the 10 min trial (Fig. 5).

Responses and swim speed

The bighead carp were significantly (Kruskal-Wallis ANOVA $P < 0.001$; Dunn's $P < 0.05$; $H = 53.478$ with 4 degrees of freedom) more reactive to the broadband sound (20.0 consecutive responses; 12.0, 23.0) than to the pure tones [500 Hz: 0.0 (0.0, 2.0); 1000 Hz: 1.0 (0.0, 2.0); 1500 Hz: 2.0 (0.0, 4.0); 2000 Hz: 1.0 (0.0, 5.0)] (Fig. 6). Behavior during the pure tone trials was inconsistent and not sustained, as the median consecutive response did not exceed 2.0 for any frequency. While the fish always retreated from the broadband sound, they responded to only 53% of pure tone presentations with one third of these trials (~17% of total) eliciting more than one reaction.

The number of reactions throughout the two-day testing period remained consistent (Fig. 7) with no significant decrease in responses between consecutive trials to the broadband sound (500 Hz: Kruskal-Wallis ANOVA $P = 0.178$; $H = 4.917$ with 3 degrees of freedom; 1000 Hz: Kruskal-Wallis ANOVA $P = 0.782$; $H = 1.079$ with 3 degrees of freedom; 1500 Hz: Kruskal-Wallis ANOVA $P = 0.887$; $H = 0.642$ with 3 degrees of freedom; 2000 Hz: Kruskal-Wallis ANOVA $P = 0.359$; $H = 3.218$ with 3 degrees of freedom; Broadband sound: Kruskal-Wallis ANOVA $P = 0.212$; $H = 4.505$ with 3 degrees of freedom). Furthermore, in 58% of tests, the carp were still responding to the broadband sound when the 10 min trials were terminated. The bighead carp demonstrated significantly faster swimming (median swim speed: 0.47 m/s; 0.36 m/s, 0.60 m/s) when moving away from the broadband sound than the pure tones or control swimming (Kruskal-Wallis ANOVA $P < 0.001$; Dunn's $P < 0.05$; $H = 80.234$ with 5 degrees of freedom) (Fig. 8).

Discussion

Throughout the experiment, the bighead carp schooled and in the absence of sound, primarily swam circular routes along the pond walls. However, their behavior changed quickly when presented with

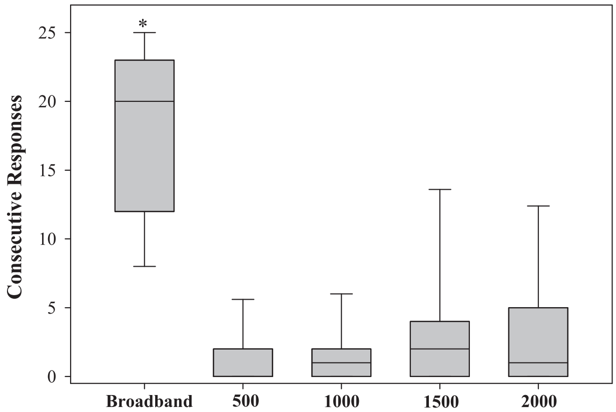

Fig. 6. Consecutive responses per trial to sound playback versus sound stimulus type (500, 1000, 1500, and 2000 Hz and broadband sound). For each box, the boundary of the box closest to zero indicates the 25th percentile, a line within the box marks the median, and the boundary of the box farthest from zero indicates the 75th percentile. Whiskers (error bars) above and below the box indicate the 90th and 10th percentiles. * indicates significantly different group (ANOVA $P < 0.001$; Dunn's $P < 0.05$; $H = 53.478$ with 4 degrees of freedom).

broadband sound, and they moved directly away from the sound source by swimming through the middle, longitudinal axis of the pond. Furthermore, the highest number of consecutive responses and the fastest swim speeds were observed when bighead carp were reacting to the broadband sound.

Pure tones, which have been historically used in non-physical fish deterrent systems either alone or in combination with bubbles and/or electric barriers (Noatch and Suski, 2012), were ineffective in producing a consistent response in bighead carp. Responses were only observed in 53% of pure tone trials, with few schools responding >2- 3 times. Vetter et al. (2015) determined that silver carp responded during 100% of the broadband sound trials (mean: 11.8 responses), but to only 12% of the pure tone presentations (<1% of these trials elicited a subsequent response). However, when presented with broadband playbacks of boat motor recordings, bighead carp showed rapid and sustained responses, with a median of 20 consecutive responses.

While the complete hearing range of bighead carp remains unknown, these fish possess Weberian ossicles, allowing relatively higher frequency hearing than many non-ostariophysan fish. Using auditory evoked potentials (AEP), Lovell et al. (2006) reported frequency sensitivity up to 3 kHz, however the tuning curve was unusually flat compared with the audiograms of other teleosts, and higher frequencies were not tested. Additionally, the study was limited due to acoustic complications with the small tank and the use of auditory evoked potentials, in which thresholds vary between studies and with behaviorally derived thresholds (Ladich and Fay, 2013; Sisneros et al., 2016). In both behaviorally based (Popper, 1972) and AEP studies (Amoser and Ladich, 2005), common carp (*Cyprinus carpio*) were found to have similar hearing sensitivities, with a maximum ranging between 0.3 and 1 kHz and a decrease in sensitivity beyond 3 kHz (see Ladich and Fay, 2013, for a review). Based on the behavior evidence reported in the current study and the sensitivities of related carp species, it appears that the pure tones and at least a portion of the broadband stimulus were within the frequency sensitivity of bighead carp as identified in Lovell et al. (2006). However, it is crucial that the upper limit of bighead carp hearing sensitivity be determined, especially since related carp species, including common carp, were much less responsive than the bighead carp to the broadband sound stimulus used in this study (Murchy et al., unpublished).

An acoustic deterrent must balance high sound pressure, which provides greater range and/or increases its efficacy, with the risk of hearing damage in fish species. Smith et al. (2004) found that goldfish exposed to 130–170 dB white noise became acclimated after 10 min of exposure and experienced hearing loss at the higher sound pressure levels; however, these experiments were conducted in much smaller tanks (19–600 L) than the present study. The maximum SPL in the experimental ponds was 156 dB re 1 μPa in a small area near the speakers where the fish spent minimal time during playback. Although it is possible that some hearing loss occurred, the bighead carp's continued phonotaxic behavior suggests fish experienced minimal impact on hearing sensitivity. Furthermore, their repeated responses indicate that the fish could locate the approximate source of the sound and/or detect the sound gradient. It also did not appear that the bighead carp were habituating to the broadband sound as the carp were still reacting to the stimulus from the active speakers in 58% of trials when the test was terminated. Additionally, there was not a significant decrease in responsiveness to the broadband sound over the two-day testing period. As both swimming duration and speed were elevated during playbacks, non-responding fish may have been fatigued rather than habituated to the sound. However, the fish did appear to habituate to the pure tones. Therefore, it is imperative that long term studies exposing both bighead and silver carp to broadband sound are conducted to determine if the fish will habituate to the broadband sound and what conditions would minimize habituation (i.e. optimal stimulus duration and interval between playbacks).

Several studies have examined non-physical barriers including acoustic barriers, either alone or in combination with bubbles, which also generate low frequency sound (Zielinski et al., 2014). Sound (20–2000 Hz) combined with a bubble curtain prevented a majority of captive bighead and silver carp crossing attempts in outdoor raceways (Pegg and Chick, 2004; Taylor et al., 2005). The same broadband sound used in the current study effectively prevented both bighead and silver carp from passing through a small opening (1 m) in a concrete barrier (Murchy et al., unpublished). These experiments demonstrate the success of sound at deterring fish in a controlled setting; however, there is little research examining the efficacy of acoustic barriers in the field. A preliminary study by Ruebush et al. (2012) used a bubble-strobe-sound (500–2000 Hz) barrier on a tributary of the Illinois River, but the researchers were unable to quantify how many fish challenged the barrier or remained in the area. The effectiveness of acoustic deterrents in winter months has been questioned due to changes in fish behavior in cold water (Hawkins and Popper, 2014). However, these behavioral changes often mean reduced activity and could result from observed decreases in metabolic processes in colder water (David, 2006; Jones et al., 2008). Silver and bighead carp are less active in colder water (Murchy, unpublished) and therefore may be less likely to challenge an acoustic barrier during the late fall through early spring.

There are limitations with this study to wild fish because of the inherent challenges in small tank acoustics and the differences between captive and wild fish behavior. Echoes are produced from interactions of the sound with the water surface and with the pond's bottom and walls, creating a complex acoustic environment for the fish to localize the sound source, even in larger concrete ponds like the one used in this study (Gray et al., 2016). Compared to field conditions, the pond is suboptimal with a complex echoic environment complicating sound localization (Gray et al., 2016) and providing limited space for the fish to escape. However, the pond's concrete composition closely replicates a lock chamber (on a smaller scale), where the technology may be eventually placed. Although there are differences in the sound field of a concrete tank when compared with a natural environment, controlled experiments can be useful to compare fish behavior when other conditions (i.e. methods, speakers, tank, fish size, etc.) remain consistent (Rogers et al., 2016), which was the case with this experiment. Therefore, despite the limitations of the small pond, the results are encouraging for the use of a broadband acoustic deterrent as part of an integrated pest management system.

Two recent reviews have cautioned against applying behavioral results from captive fish to those in the wild (Popper et al., 2014; Hawkins et al., 2015). However, preliminary results from a field study

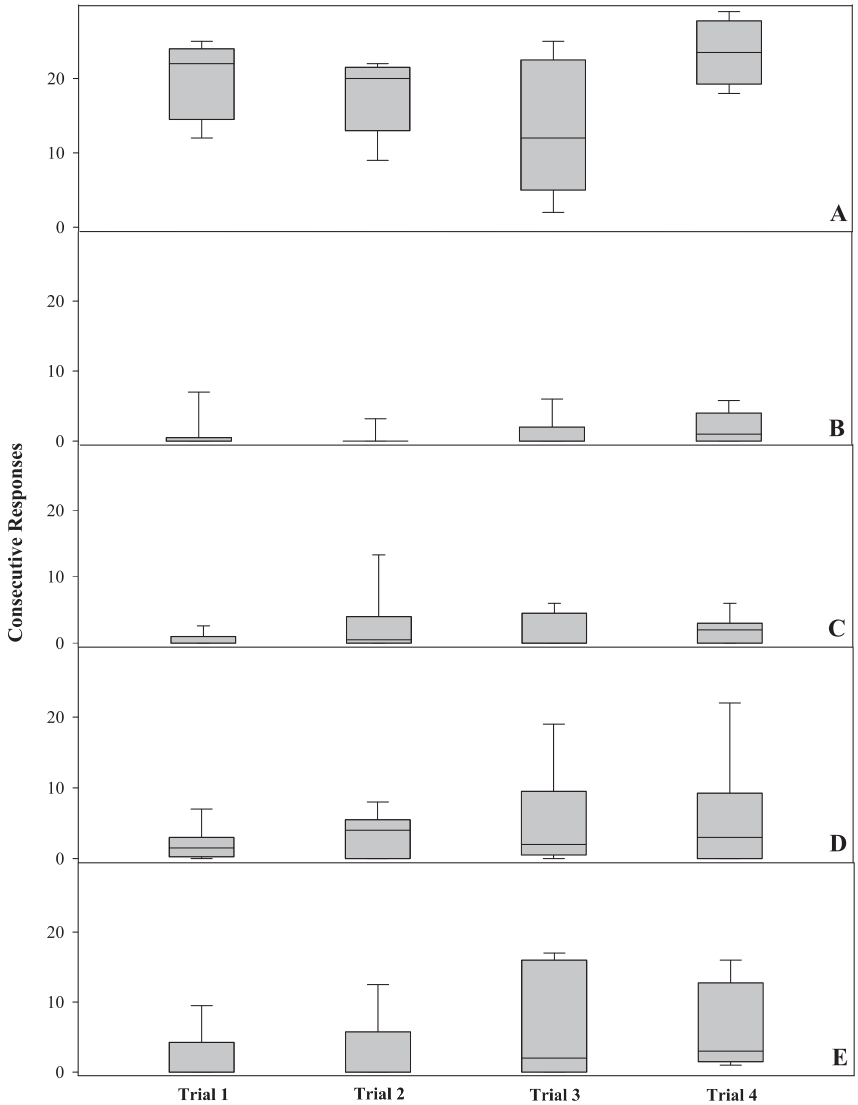

Fig. 7. Number of consecutive responses over time for each sound stimulus type: A) 500 Hz, B) 1000 Hz, C) 1500 Hz, D) 2000 Hz, E) Broadband sound. The boundary of the box closest to zero indicates the 25th percentile, a line within the box marks the median, and the boundary of the box farthest from zero indicates the 75th percentile. Whiskers (error bars) above and below the box indicate the 90th and 10th percentiles. Boxes compare the number of consecutive responses by bighead carp to the first, second, third, and fourth presentation of each stimulus type. There is no significant difference between the trials (500 Hz: ANOVA $P = 0.178$; $H = 4.917$ with 3 degrees of freedom; 1000 Hz: ANOVA $P = 0.782$; $H = 1.079$ with 3 degrees of freedom; 1500 Hz: ANOVA $P = 0.887$; $H = 0.642$ with 3 degrees of freedom; 2000 Hz: ANOVA $P = 0.359$; $H = 3.218$ with 3 degrees of freedom; Broadband sound: ANOVA $P = 0.212$; $H = 4.505$ with 3 degrees of freedom).

that exposed resident silver and bighead carp in the Spoon River near Havana, IL to broadband sound, demonstrated that silver carp jump in response to the acoustic stimulus alone (Vetter, unpublished). Furthermore, concurrent sonar indicated that all putative carp (species identification was not possible) exited the area and that the sound could displace fish at least 200 m from the source (Mensinger, unpublished). This suggests that sound could be effective in modulating wild fish behavior and provides a strong argument for further research exploring the efficacy of acoustic deterrents in carp infested waters. The pond was modest in size and prevented fish from swimming >9.0 m from the source and the continual alternation of the sound source probably generated fatigue in a portion of the schools, neither of which would be a factor with longer distance repulsion and less frequent sound exposure in a natural setting.

Playback of the outboard motor recording through the UW-30 did modify the sound due to the speaker characteristics, however the goal of the study was to identify sound that caused consistent negative phonotaxis and not rebroadcast the exact sound spectrum of the outboard motor in high fidelity. The playbacks were effective in accomplishing the goals of the study. Additionally, while particle motion, which was not measured in this study, may have given greater insights the acoustic environment in the pond, it was not necessary to accomplish the experimental objectives. Furthermore, future deterrents will be tested in much larger ponds or in the field and the same particle motion environment of a small pond would be difficult to recapitulate. However, it is important that the ambient sound field of the river be determined in field sites where broadband sound is tested or implemented as part of a deterrent barrier.

Bighead and silver carp are closely related, co-exist in the wild, and hybridize. However, silver carp can be readily stimulated to jump by boat traffic, electric shock, or loud sound, making it relatively easy to locate their presence. Even small silver carp (<10 cm sl) in relatively low densities (single fish jumping) have been observed to jump (Mensinger, unpublished). In turbid waters, it is difficult to assess the number of bighead carp, as they do not jump. To effectively manage both species, the response behavior of bighead carp must also be determined. This study suggests that, similar to silver carp, bighead carp swimming is also modulated by broadband sound.

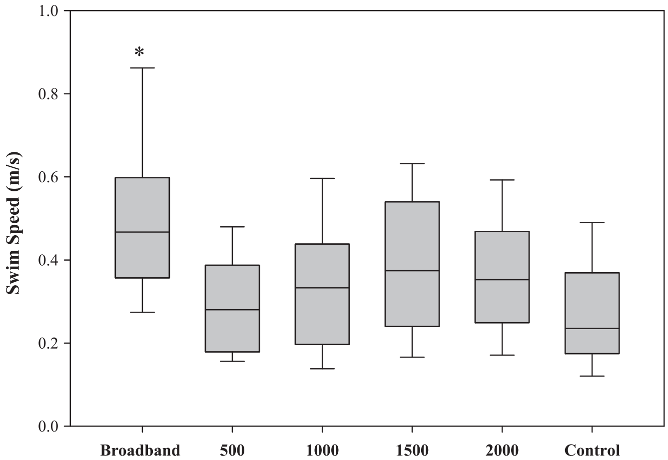

Fig. 8. Fish swim speeds. Box and whisker plots display the median swim speed while the bighead carp were retreating from the sound stimuli. Swim speed was calculated by determining the time the fish swam the first 2.0 m away from the sound source. The control represents the average time for fish to swim 2.0 m in the absence of sound. The boundary of the box closest to zero indicates the 25th percentile, a line within the box marks the median, and the boundary of the box farthest from zero indicates the 75th percentile. Whiskers (error bars) above and below the box indicate the 90th and 10th percentiles. * indicates significantly different group (ANOVA $P < 0.001$; Dunn's $P < 0.05$; $H = 80.234$ with 5 degrees of freedom).

Finally, it is important to determine the impact of broadband sound on native species prior to field implementation. Preliminary studies suggest that many native species, including game fish (walleye, *Sander vitreus*; bluegill, *Lepomis macrochirus*; and rainbow trout, *Oncorhynchus mykiss*), channel catfish (*Ictalurus punctatus*), fathead minnow (*Pimephales promelas*), lake sturgeon (*Acipenser fulvescens*), paddlefish, gizzard shad, and bigmouth buffalo do not demonstrate a behavioral response to the same sound used in this study (Murchy, unpublished). This is especially interesting since bigmouth buffalo are ostariophysans and gizzard shad are clupeids, both of which can detect high frequency. However, many native species do not have specialized hearing structures, like the Weberian ossicles found in bighead carp, and therefore cannot detect higher frequency sounds. Lovell et al. (2005) examined paddlefish and lake sturgeon hearing and reported low thresholds between 200 and 300 Hz. Furthermore, other non-native carp, such as grass (*Ctenopharyngodon idella*) and common carp (Murchy, unpublished), also do not demonstrate the degree of negative phonotaxis seen in silver carp (Vetter et al., 2015) or the bighead carp in this study. Therefore, a refined broadband sound that targets the peak frequency sensitivity of bighead and silver carp could be effective in targeting these species with minimal impact on native species, as suggested in the Lovell et al. (2005) study.

Acoustic deterrents could be an effective means to herd or prevent upstream migration of both bighead and silver carp. While physical and electric barriers are expensive and not always practical, an acoustic deterrent has many applications. For instance, speakers playing a broadband sound stimulus could be used to move bighead and silver carp towards a net or shore, clear fish out of a lock before allowing a ship to pass through, or as reinforcement to an electric barrier during routine maintenance when the field is not active. The range expansion of invasive bighead and silver carp is a concern to many state and federal agencies as the fish threaten their environments. This study indicates that because bighead and silver carp (Vetter et al., 2015) are similarly responsive to broadband sound, the species can be co-managed and that broadband sound may be an important management tool which could be effective either on its own or integrated with other deterrent technology. These closely related species are already treated as one because of their population overlap and genetic relationship. The similar responses of bighead and silver carp to broadband sound stimuli suggest that incorporation of these sounds into the integrated pest management programs of natural resource agencies may be successful in altering fish behavior.

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