

Acoustical deterrence of Silver Carp (*Hypophthalmichthys molitrix*)

Brooke J. Vetter · Aaron R. Cupp ·
Kim T. Fredricks · Mark P. Gaikowski ·
Allen F. Mensinger

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Abstract The invasive Silver Carp (*Hypophthalmichthys molitrix*) dominate large regions of the Mississippi River drainage and continue to expand their range northward threatening the Laurentian Great Lakes. This study found that complex broadband sound (0–10 kHz) is effective in altering the behavior of Silver Carp with implications for deterrent barriers or potential control measures (e.g., herding fish into nets). The phonotactic response of Silver Carp was investigated using controlled experiments in outdoor concrete ponds (10 × 4.9 × 1.2 m). Pure tones (500–2000 Hz) and complex sound (underwater field recordings of outboard motors) were broadcast using underwater speakers. Silver Carp always reacted to the complex sounds by exhibiting negative phonotaxis to the sound source and by alternating speaker location, Silver Carp could be directed consistently, up to 37 consecutive times, to opposite ends of the large outdoor pond. However, fish habituated quickly to pure tones, reacting to only approximately 5 % of these presentations and never showed more than two consecutive responses. Previous studies have

demonstrated the success of sound barriers in preventing Silver Carp movement using pure tones and this research suggests that a complex sound stimulus would be an even more effective deterrent.

Keywords Silver Carp · Acoustics · Phonotaxis · Deterrent barriers · Management · Behavior

Introduction

Silver Carp (*Hypophthalmichthys molitrix*) were introduced to aquaculture facilities in the southern region of the United States from eastern Asia in the 1970's (Kolar et al. 2005). The carp initially were used as a biological method of controlling algal growth in sewage treatment and fish farming facilities. Through a series of flooding events, the fishes subsequently escaped and established populations throughout the Mississippi River Basin and are currently threatening the Laurentian Great Lakes (Sass et al. 2010; Murphy and Jackson 2013). Carp have negatively impacted native fish 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) due to their fast growth, prolific spawning, and ability to outcompete native fish for food and space. Additionally, Silver Carp demonstrate an unusual jumping behavior, which presents a hazard to boaters.

B. J. Vetter (✉) · A. F. Mensinger
Biology Department, University of Minnesota Duluth,
1035 Kirby Drive, Duluth, MN 55812, USA
e-mail: vett0114@d.umn.edu

A. R. Cupp · K. T. Fredricks · M. P. Gaikowski
Upper Midwest Environmental Sciences Center, United
States Geological Survey, 2630 Fanta Reed Road,
La Crosse, WI 54603, USA

Invasive Silver Carp continue to migrate northwards through the Mississippi River Basin and expand their range via interconnected waterways, impeded only by large physical barriers. The Laurentian Great Lakes are currently threatened as these carp have been found in shipping canals that connect the Illinois River and Lake Michigan (Moy et al. 2011). Additionally, prevention efforts are ongoing to prevent Silver Carp expansion into Mississippi River tributaries and lakes (Kelly et al. 2011). Considerable effort has gone into erecting electric barriers on the Chicago Ship and Sanitary Canal to prevent spread into Lake Michigan, however, electrical barriers have inherent risks and must be continuously operated to prevent upstream migration (Clarkson 2004). Non-physical barriers, such as noxious sound stimuli, are promising methods that can be deployed in addition to electric barriers or when such systems are not feasible (Noatch and Suski 2012).

Since the early 1950's, researchers have examined sound to control fish movement (Burner and Moore 1953). Historically, research efforts have focused on using acoustic deterrents to prevent fish from entering hydropower dams or power plants (Schilt 2007). Ultrasound (122–128 kHz) was 87 % effective in preventing Alewives (*Alosa pseudoharengus*) from approaching a dam intake in Lake Ontario (Ross et al. 1993). Maes et al. (2004) used a variety of frequencies (20–600 Hz) to repel Atlantic Herring (*Clupea harengus*, 94.7 %) and European Sprat (*Sprattus sprattus*, 87.9 %) from a power plant intake. In the past 20 years, acoustic deterrents, often coupled with bubbles or lights, have been used to modulate invasive fish behavior with the intent on preventing their range expansion (Noatch and Suski 2012). Pegg and Chick (2004) found 20–2000 Hz sound was more effective (95 %) in preventing Silver and Bighead (*Hypophthalmichthys nobilis*) Carp from crossing a bubble-sound barrier than frequencies in the 20–500 Hz range (57 % effective). Similarly, sound (20–2000 Hz) combined with a bubble curtain, successfully repelled Bighead Carp (95 %) in an enclosed raceway (Taylor et al. 2005). Sound (500–2000 Hz), bubbles, and light impeded the upstream migration of Silver and Bighead Carp in a small tributary (Ruebush et al. 2012). Laboratory experiments demonstrate that bubble curtains, which generate 200 Hz frequency sound, can inhibit movement of Common Carp (*Cyprinus carpio*) (75–85 %) (Zielinski et al. 2014). While strobe lights have some success in affecting fish movement, they

also appear more effective when paired with sound or bubbles (Noatch and Suski 2012). These studies demonstrate the potential of acoustic deterrents for modulating fish behavior.

For sound barriers to be effective, fish must be able to detect the frequency, localize the sound source, and stop or move away from the source. Silver Carp are cyprinids in the superorder ostariophysi, which possess Weberian ossicles that form a connection between the swim bladder and inner ear (Popper and Carlson 1998; Fay and Popper 1999). These ossicles provide Silver Carp with relatively broad hearing (up to at least 3 kHz) and greater sensitivity than many other Midwestern and Great Lakes fishes that lack the connection (Lovell et al. 2006). For example, Lake Sturgeon (*Acipenser fulvescens*) and Paddlefish only detect sounds up to approximately 400 Hz, with peak sensitivity between 200 and 300 Hz (Lovell et al. 2006), and the frequency sensitivity of Bluegill Sunfish (*Lepomis macrochirus*) is 200–300 Hz (Scholik and Yan 2002a). Other carp species have demonstrated the ability to detect and/or localize sound stimuli associated with food reward. Grass Carp (*Ctenopharyngodon idella*) (Willis et al. 2002) were trained to localize pure tones (600–1000 Hz) and carp feeding sounds, and Common Carp (Sloan and Mensinger 2013) were classically conditioned to associate feeding with a 400 Hz pure tone. Therefore, the use of higher frequency sounds for Silver Carp management has the potential to modulate carp behavior while minimizing the effect on native game fish.

Previous studies on effective sound barriers utilized pure tone stimuli. The present study investigated both pure tones (0.5–2 kHz) and higher frequency (0–10 kHz) complex sound on Silver Carp behavior during a set of controlled experiments in outdoor concrete ponds. The goal was to determine the optimal frequency or frequencies for deterring Silver Carp movement and it was predicted that the complex sound stimulus would be more successful in affecting fish swimming behavior.

Material and methods

Animal husbandry

All experiments were conducted at the Upper Midwest Environmental Sciences Center (UMESC) of the

United States Geological Survey (USGS) in La Crosse, WI. Silver Carp (18–24 cm) 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 US Government). All experimental fish were tagged with passive integrated transponder (PIT) tags (Biomark Inc, Boise, ID) at least 1 week prior to experimentation. During the tagging process, fish were sedated with 100 mg/L AQUI-S[®] 20E (10 mg/L eugenol) (AQUI-S New Zealand Ltd., Lower Hutt, New Zealand) in the culture pond to minimize jumping when removed for tagging. Fish were hand netted from the culture pond and then placed in 300 mg/L AQUI-S[®] 20E (30 mg/L eugenol) until loss of equilibrium and failure to respond to caudal peduncle pinch. Each fish was wiped with 1 % topical iodine and injected with PIT tags into the abdomen about 2 cm anterior to the vent and placed in fresh flowing water to recover. To facilitate transport to the pond, fish (N = 10) were sedated with 50 mg/L AQUI-S[®] 20E (5 mg/L eugenol) to minimize jumping and potential injury. Food was withheld for 24 h prior to transport and fish were not fed while in the outdoor ponds (<7 days). Each group (N = 5) was allowed to acclimate in the outdoor pond for at least 48 h prior to the initiation of experiments. Two-day trials were conducted from July through September 2013.

Behavioral experiments

Behavioral experiments were conducted in 10 m × 5 m × 1.2 m (60 k L) outdoor concrete flow through ponds (Fig. 1). Flow rate into the ponds was adjusted to maintain a water temperature range of 17–21 °C. Water was pumped into the ponds directly from UMESC wells. Although water quality was not measured, fish showed no signs of being stressed due to poor water quality. Each pond was fully enclosed vertically by a 2 m wire fence on the top of the pond walls with anti-bird netting draped across the top of the fence. Pond access was restricted to a 2 m × 1 m wire door that remained locked throughout the experiment.

Sound stimuli

Sound was delivered via one of two pairs of underwater speakers (UW-30, Lubell Labs Inc., Whitehall,

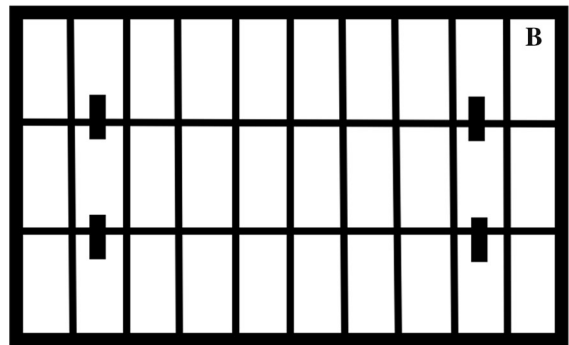
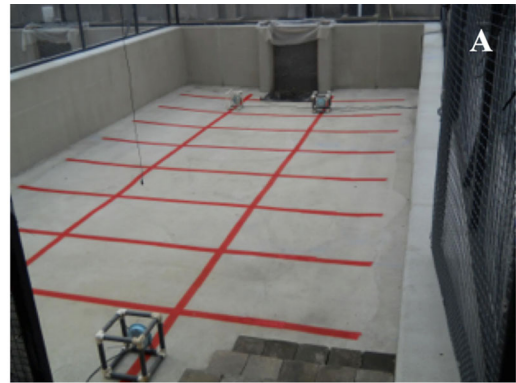


Fig. 1 **a** View from the entry door of a drained experimental pond. Speakers are at the near (only one visible) and the far (pair) end of the pond. Water level was maintained within 5 cm of the top of the concrete walls. The fence enclosing the pond is visible at the top of the walls. Gridlines painted on pond bottom assisted in assessing fish position. **b** Overhead schematic of the experimental pond showing approximate location of gridlines and speakers (*solid rectangle*)

OH) that were placed 1.5 m from each end of the pond and 1.6 m from the nearest side-wall (Fig. 1). Acoustic stimuli consisted of pure tones (500, 1000, 1500, or 2000 Hz) generated by Audacity 2.0.5 software and complex tones recorded underwater from an outboard motor (100 Hp Honda 4-stroke). The outboard motor sound was recorded using a hydrophone (HTI-96-MIN, High Tech Inc., Long Beach, MS), in a section of the Illinois River near Havana, IL, which contained Silver Carp populations. The sound was recorded in approximately 1 m of water while the boat transited past the hydrophone at 32 km/h, which also stimulated carp to jump in the area.

Sound was amplified (UMA-752 amplifier, Peavey Electronics, Meridian, MS) and each speaker pair was controlled manually with a switchbox (MCM Electronics, Centerville, OH). Each pond contained a

single hydrophone (HTI-96-MIN, High Tech Inc., Long Beach, MS) to verify the sound stimuli, which was recorded using a PowerLab 4SP data acquisition system and LabChart 7 software (AD Instruments, Colorado Springs, CO).

Sound pressure levels were maintained constant for the pure tones and complex sound and were approximately 150 dB re 1 μ Pa @ 1 m directly in front of the speakers, which was approximately 30 dB re 1 μ Pa @ 1 m above the minimum ambient noise (Fig. 2). All pure tone responses showed a narrow energy peak at the dominant frequency (Fig. 3). The complex sound produced a broad spectrum of sound from 0 to 10 kHz with maximal energy contained in two relatively broad peaks from 0 to 2 kHz and 6 to 10 kHz (Fig. 3).

Behavior was monitored remotely with eight overhead SONY bullet 500 TVL video cameras connected to ProGold software (Security Camera World, Cooper City, FL). An observer was situated in a shelter approximately 50 m from the test pond. The cameras continuously monitored the fish and provided full coverage of the pond. Gridlines (1.6 m \times 1.0 m) on the pond bottom (Fig. 1) assisted in determining fish position.

Silver Carp demonstrated schooling behavior and therefore the group of fish in each trial was treated as a single unit with position determined as the approximate center of the school. Trials (i.e., sound stimuli) were not initiated until the school was positioned within an end zone, which was defined as the area of the pond within 2.5 m of the end wall.

The experimental trials consisted of playing sound from one speaker pair, observing the behavioral

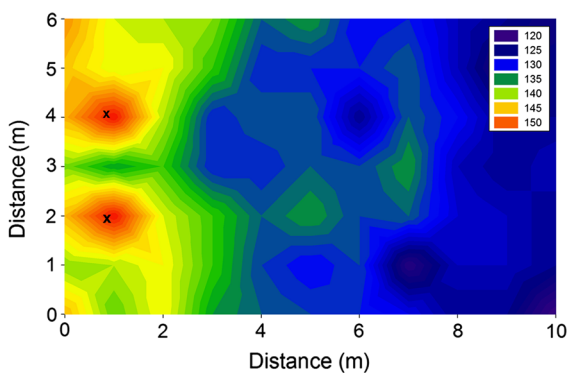


Fig. 2 The sound intensity level (dB re 1 μ Pa @ 1 m) is plotted during active broadcast of the two underwater speakers (indicated by X). Recordings were made at 1 m intervals and a depth of 0.6 m. Intensity level is indicated by color in upper right inset

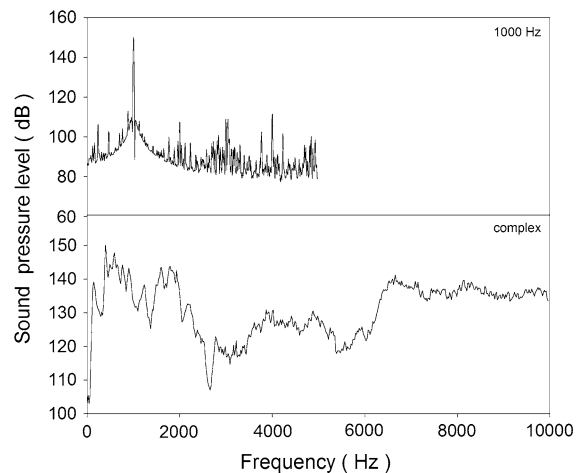


Fig. 3 The power spectrum in dB of the 1000 Hz and complex sound stimulus is plotted versus frequency (Hz)

response, and alternating the sound location if the fish swam away from the sound. Negative phonotaxis was defined as the group of fish orienting and swimming away from the end zone closest to the sound source within the first 15 s of sound onset and crossing the centerline (5 m) within 30 s. During these responses, the observer would continue to administer sound until fish reached the far end zone. Once the fish entered the opposite end zone from the midline, the sound source was changed to the speakers in that end zone. All behaviors not conforming to the criteria established for a negative phonotaxis, such as no reaction, swimming towards the speaker, or failure to cross the midline in 30 s, were categorized as no response. Consecutive responses were defined as fish reacting to two or more consecutive sound presentations from opposite ends to the pond. Sound trials were conducted with pure tones and complex sounds with the order of presentation (pure tones vs. complex) randomly determined prior to each trial. Trials were completed over a 2-day period for each of the five groups of fish with 3–4 pure tone and 4–11 complex sound trials conducted on each group.

Pure tone trials

Fish position was monitored for 10 min prior to initiation of sound. Each trial began with a 30 s pure tone (500, 1000, 1500 or 2000 Hz) initiated from the nearest speaker pair to the fish. Once the fish failed to respond, the sound was terminated and the fish were

allowed a recovery time of 90–180 s before the next sound presentation of the same frequency. Each trial consisted of three to five presentations of the same frequency and was concluded with 30 s of continual complex sound (outboard motor underwater recording). For both the pure tone and complex sound presentation, the sound source was alternated if the fish reacted to the sound and crossed into the opposite end zone. Fish were allowed to rest for 10–15 min after the presentation of the complex sound at the conclusion of the pure tone trial, before a different frequency was tested using the same procedure. The four frequencies were tested consecutively with presentation order of the frequencies randomized. Fish were allowed to rest for at least 30 min after each set of all four frequencies was tested before subsequent sound trials (pure tone or complex).

Complex sound trials

Complex sound trials were conducted following a similar protocol with the underwater recording of an outboard motor used as the stimulus. Preliminary trials showed that this stimulus produced consistent and repeated negative phonotaxis so the protocol was modified slightly, and the 30 s complex sound file was continuously looped throughout the trial. The sound stimulus was switched to the opposite speaker pair as soon as the school crossed into the opposite end zone. Based on fish response and position, the sound source was alternated for 10 min or until the fish failed to respond. Fish were allowed to rest for at least 1 h after each complex sound trial before any other sound trials were conducted.

Data analysis

Fish position was monitored from 10 min prior to and throughout the sound presentation for sound trials. The position of the midpoint of the school was recorded 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/s). The elapsed time from when the fish turned away from the sound and swam 2 m away was calculated. The swim speeds were only assessed when the group of fish turned in response to sound playback and swam the 2 m in <30 s. In order to accurately compare response

times, groups that took longer than 30 s, or did not respond, were excluded from analysis. Control swim speeds were determined prior to testing or at least an hour after fish had been exposed to sound by monitoring. For a control, fish were observed for a 10-min period of continuous swimming in the absence of sound and the duration that it took the school to transverse each 2 m interval was recorded and averaged.

Sound mapping

Acoustic properties of the speakers and pond were mapped using an HTI hydrophone connected to the PowerLab 4SP data acquisition system and LabChart 7 software. The pond was divided into a 1 m × 1 m grid and a total of 77 recordings were made at 1 m intervals. Relative sound pressure levels (SPL) were calculated for each frequency by measuring the root mean square (rms) voltage and converting to SPL in dB re 1 μ Pa @ 1 m using Avisoft-SASLab Pro ver 5.2.07. The frequency components and power spectrum of the sound were calculated with a 1024-point fast Fourier transform (Hamming window) and sampling rate of 40 kHz.

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 and therefore non-parametric Kruskal–Wallis ANOVAs with Dunn’s post hoc tests were used to analyze the data. Although the response data were analyzed using non-parametric tests, the mean \pm 1 SE is reported for illustrative purposes as the median and quartiles for the pure tone frequencies were all 0. The median and upper and lower quartile is reported for the swim speeds ($P < 0.05$).

Results

Behavioral responses

Fish behavior, in the absence of sound, alternated between slow swimming throughout the pond (one circuit approximately every 2 min) and remaining in one location, typically a shady area of the pond. For pure tones trials, fish demonstrated negative phonotaxis to approximately 12 % of the initial sound

presentations, with <1 % of the pure tone stimuli trials eliciting a subsequent reaction from the fish and zero responses to three or more consecutive presentations (Fig. 4). However, the fish always displayed negative phonotaxis when subjected to the complex sound at the conclusion of each trial. Fish were slightly more responsive to higher frequencies, showing an average of 0.18 ± 0.06 responses to 2000 Hz compared 0.13 ± 0.06 reactions for the 500 Hz. In contrast, the Silver Carp responded during 100 % of the complex trials with an average of 11.8 ± 1.3 (range 3–37) consecutive responses per trial. Furthermore, the number of average consecutive responses to the complex sound was significantly greater ($H = 144.06$, $P < 0.001$) than in the pure tone trials.

Representative Silver Carp behavior to acoustic stimulation from two of the five groups is displayed in Fig. 5. Controls demonstrate the typical slow swimming over the course of 10 min in the absence of sound stimuli (Fig. 5 control). Group A did not respond to the 500 and 1000 Hz and at the two higher frequencies (1500 and 2000 Hz), the fish responded to only the second of three pure tone presentations. Similarly, for Group B, the fish did not respond to pure tones at the 500, 1000, and 2000 Hz frequencies. During the first, second, and third 1500 Hz pure tone presentations, Group B demonstrated one response. In contrast, both groups responded to the complex sound after all the pure tone presentations. Consistent back and forth swimming along the length of the pond away from the active speaker pair during complex sound

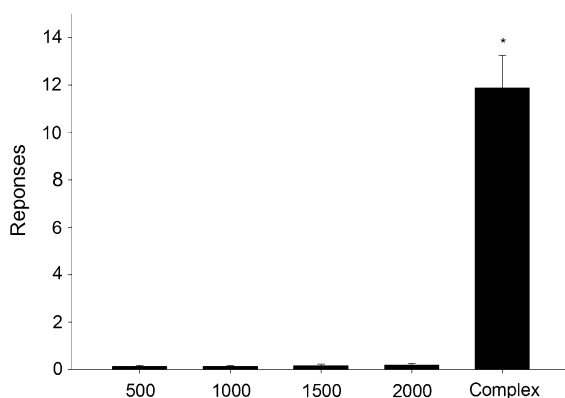


Fig. 4 Average number of responses per trial to sound playback versus sound stimulus type (500, 1000, 1500, and 2000 Hz and complex sound). All data show the mean \pm 1 standard error. Asterisk indicates significantly different group ($P < 0.001$)

trials was observed (Fig. 5 complex) with Group B demonstrating 37 consecutive negative phonotactic responses to the complex sound. Following the fourth sound presentation, Group A swam to the opposite wall of the pond but remained behind the speakers. They remained at this end for about a minute but then continued to react to the complex sound stimuli, demonstrating 26 consecutive responses for a total of 31 responses during this trial.

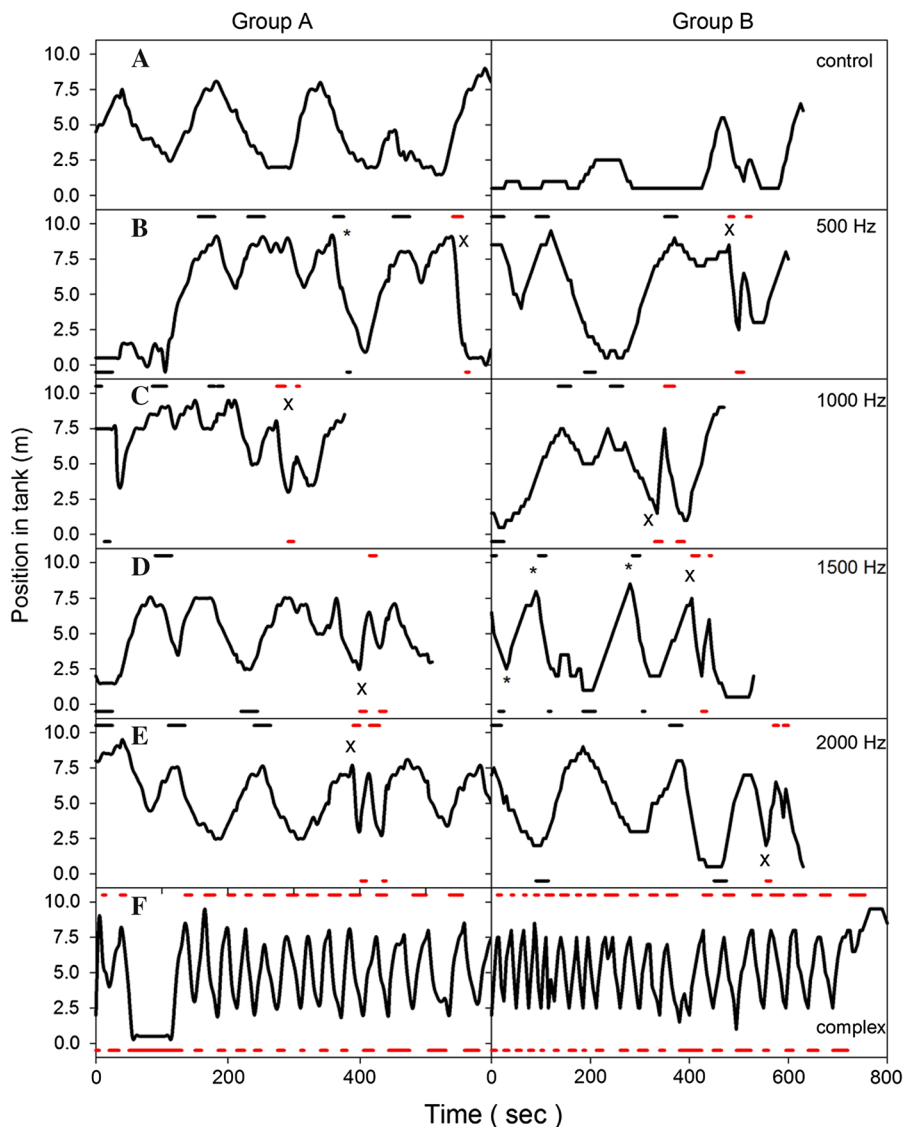
Fish averaged approximately 13 s to swim 2 m (0.15 m/s) during the times they were actively swimming in the absence of sound (Fig. 6). Median times for fish to respond to pure tones ranged from 9.2 (1500 Hz) to 26.0 s (2000 Hz) (0.22 to 0.08 m/s), while fish reacting to the complex sound swam away significantly faster with a median time of 4.8 s ($H = 75.306$, $P < 0.001$) or 0.42 m/s.

Discussion

Silver Carp demonstrated consistent movement away from complex sounds whereas pure tones were less successful in eliciting a reaction. At best, fish responded to two consecutive pure tones, but failed to react to over 95 % of the presentations. Conversely, the complex sound alone was sufficient to reliably drive carp away from the source eliciting an average of eleven consecutive responses. This suggests that complex broadband sound (0–10 kHz), such as the outboard motor recording used, is more effective in affecting Silver Carp swimming than pure tones.

The Silver Carp habituated quickly to the pure tones as they demonstrated the characteristic decrease in responsiveness upon repeated exposure to the stimuli (Rankin et al. 2008; Thompson and Spencer 1966). For the complex sound, the fish usually stopped responding by the end of the 10 min test period but it was unclear whether this was due to habituation or fatigue. In contrast to the pure tones, subsequent playbacks of the complex sound, after a recovery period, continued to elicit a response. This suggests that fatigue may have factored into reduced responses as the fish continually reacted to the alternating complex sound source at a significantly greater swim speed than during the pure tones or controls. Furthermore, despite repeated trials, the schools would still respond to at least three consecutive sound presentations. Finally, the decreased responsiveness to pure

Fig. 5 Representative Silver Carp behavioral response to acoustic stimulation for two groups of fish (*Group A* and *Group B*). For each figure, 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* indicates pure tones and *red* indicates complex motor sounds. *Asterisk* indicates no response and *X* represents negative phonotaxis; in situations where the fish demonstrated consecutive responses, the first response is indicated by an *X*. **a** control (no sound); **b** 500 Hz; **c** 1000 Hz; **d** 1500 Hz; **e** 2000 Hz; **f** complex sound



tones was behaviorally based as subsequent playbacks of the complex sound resulted in rapid movement away from the sound, indicating that the auditory system was functional and the fish were able to locate the sound source.

Both the pure tones and a portion of the complex stimulus used in this study were within the known frequency sensitivity of Silver Carp (up to 3 kHz) and the intensities presented were well above their auditory thresholds (Lovell et al. 2006). Although the typical c-start startle response characterized by rapid contraction of the axial muscles and movement away from the stimulus was sometimes observed at the first

sound presentation (video quality and speed was insufficient to quantify c-start mechanics), subsequent responses did not elicit this behavior. Thus, the prolonged negative phonotaxis exhibited appeared to be directed swimming behavior away from the complex sound and not a sudden or rapid escape response.

The effects of high frequency anthropogenic sound on native ostariophysans, such as minnows, suckers, and catfish, remains to be determined. In a laboratory study involving Fathead Minnows (*Pimephales promelas*), exposure to white noise (0.3–4.0 kHz dB re μ l Pa) significantly increased auditory thresholds, especially in the higher frequency range (0.8–2.0 kHz)

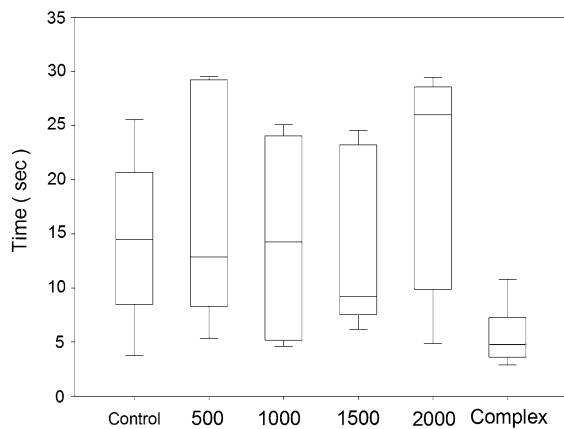


Fig. 6 Fish swim speeds. *Box* and *whisker* plots display the median and upper and lower quartile for the time for fish to swim 2 m after sound stimulation. The control represents the average time (<30 s) to swim 2 m in the absence of sound ($P < 0.001$)

and persisted for at least 14 days after exposure (Scholik and Yan 2001). Anthropogenic noise is also thought to affect fish behavior. For example, Blacktail Shiners (*Cyprinella venusta*) increased the amplitude and rate of mating calls in the presence of background noise (Holt and Johnston 2014). One of the most prominent sources of anthropogenic noise is recreational and commercial motorized watercraft and negative effects of these sounds on fish are well documented (Scholik and Yan 2002b; Liu et al. 2013; Voellmy et al. 2014; Popper and Hastings 2009; Whitfield and Becker 2014). More research on the effect of high frequency sound on native species, especially ostariophysans, is essential before acoustic deterrents can be implemented.

The impetus to determine if sound could be used to modulate behavior was based on the jumping behavior of Silver Carp in response to motorized watercraft and anecdotal reports of commercial fisherman using noise to concentrate fish for capture. Although their propensity for jumping has been well documented, especially in popular videos, few if any studies address the sensory input that elicits this behavior. Understanding the behavior and sensory physiology of an invasive fish species is imperative when developing methods to for management and control (Popper and Carlson 1998).

The Silver Carp in the current study did not jump in response to sound. Fish have been documented to jump using higher intensity sound in the Illinois River in the absence of motorized watercraft, however

they tended to be larger than the fish used in this study (Mensinger, unpublished). Furthermore, the water clarity was also much higher in the outdoor ponds compared to the Illinois River (Arnold et al. 1999). Increased turbidity may enhance the tendency of Silver Carp to jump, as it reduces the fish's visual field. It is unclear whether boat movement and/or waves plus sound is the basis for this behavior. It should also be noted that each group of fish was naïve to the sound stimuli. Furthermore, the fish were collected as young of the year and reared in the lab so any exposure to outboard motors would have been limited to their early life history.

Previous studies have investigated sound to control both Bighead and Silver Carp using primarily pure tones. Taylor et al. (2005) tested a bubble-curtain barrier combined with a random sound generator (pure tones from 20 to 2000 Hz) in outdoor experimental raceways and reported that the bubble-sound barrier was effective at preventing 95 % of the Bighead Carp's attempts to cross. Ruebush et al. (2012) used a bubble-strobe-sound (500–2000 Hz) barrier on a tributary of the Illinois River and assessed the number of marked Silver and Bighead Carp that crossed the barrier while migrating upstream. Only two tagged Silver Carp ($N = 575$) and no Bighead Carp ($N = 101$) crossed the barrier; however it was unclear how many fish challenged the barrier or remained in the area.

Lovell et al. (2006) demonstrated that Silver Carp respond to frequencies up to 3 kHz, however as their hearing sensitivity decreased relatively slowly at the higher frequencies tested, the fish may retain higher frequency sensitivity past the end point (3 kHz) of their study. Therefore, the carp were able to detect the complex sound stimulus. The results suggest that complex sound, containing frequencies from 0 to 10 kHz, is capable of consistently modulating behavior and has potential to be developed as part of an acoustic or multi-modal deterrent system. An acoustic deterrent has advantages over electrical or physical barriers in that sound can travel a considerable distance underwater, poses minimal environmental risk, and is relatively inexpensive to deploy. Furthermore, a barrier that uses this complex sound, either alone or in combination with light and bubbles, is an ideal strategy to restrict Silver Carp range expansion because the higher frequency components target Silver Carp, and will have minimal, if any, impact

on most native game fish, though further testing is needed to evaluate the effect on native ostariophysans. Research examining the efficacy of a sound deterrent in an open rather than closed system is also necessary, as the Silver Carp had limited (<10 m) distance to escape the sound in the experimental ponds. An open system, such as a river, might allow the Silver Carp to swim a greater distance from the sound and could lengthen the time that the fish would stay away. Ruebush et al. (2012) reported that many carp moved back down stream, away from their bubble-strobe-sound barrier and out of the study system. A barrier using the complex sound stimuli might have a similar effect as wild fish can leave the area.

The range expansion of invasive Silver Carp is a concern to many state and federal agencies as the fish threaten entire food webs and the jumping behavior of Silver Carp endangers recreational and commercial boaters. This study's objective was to determine the effects of sound on modulating Silver Carp behavior. The results suggest that the complex sound may be an important management tool and could be effective either on its own or integrated with other deterrent technology.

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References

Arnold TL, Sullivan DJ, Harris MA, Fitzpatrick FA, Scudder BC, Ruhl PM, Hanchar DW, Stewart JS (1999) Environmental setting of the upper Illinois River basin and implications for water quality. US Department of the Interior and US Geological Survey National Water-Quality Assessment Program Water-Resources Investigations Report 98-4268

Burner CJ, Moore HL (1953) Attempts to Guide Small Fish with Underwater Sound. US Department of the Interior Special

Scientific Report: Fisheries No. 111. US Department of the Interior

Clarkson RW (2004) Effectiveness of electrical fish barriers associated with the Central Arizona Project. *N Am J Fish Manag* 24(1):94–105

Fay RR, Popper AN (1999) The auditory periphery in fishes. In: Fay RR, Popper AN (eds) *Comparative hearing: fish and amphibians*. Springer, New York, pp 43–100

Holt DE, Johnston CE (2014) Evidence of the Lombard effect in fishes. *Behav Ecol* 25(4):819–826

Irons KS, Sass GG, McClelland MA, Stafford JD (2007) Reduced condition factor of two native fish species coincident with invasion of non-native Asian carps in the Illinois River, USA—is this evidence for competition and reduced fitness? *J Fish Biol* 71:258–273

Kelly AM, Engle CR, Armstrong ML, Freeze M, Mitchell AJ (2011) History of introductions and governmental involvement in promoting the use of grass, silver, and bighead carps. In: Chapman DC, Hoff MH (eds) *Invasive Asian Carps in North America*. American Fisheries Society, Symposium, 74. Bethesda, MD, pp 163–174

Kolar KS, Chapman DC, Courtenay WR Jr, Housel CM, Williams JD, Jennings DP (2005) Asian carps of the genus *Hypophthalmichthys* (Pisces, Cyprinidae)—a biological synopsis and environmental risk assessment. US Fish and Wildlife Service

Liu M, Wei QW, Du H, Fu ZY, Chen QC (2013) Ship noise-induced temporary hearing threshold shift in the Chinese sucker *Myxocyprinus asiaticus* (Bleeker, 1864). *J Appl Ichthyol* 29:1416–1422

Lovell JM, Findlay MM, Nedwell JR, Pegg MA (2006) The hearing abilities of the silver carp (*Hypophthalmichthys molitrix*) and bighead carp (*Aristichthys nobilis*). *Comp Biochem Physiol A: Mol Integr Physiol* 143(3):286–291

Maes J, Turnpenny AWH, Lambert DR, Nedwell JR, Parmentier A, Ollevier F (2004) Field evaluation of a sound system to reduce estuarine fish intake rates at a power plant cooling water inlet. *J Fish Biol* 64(4):938–946

Moy PB, Polls I, Dettmers JM (2011) The Chicago sanitary and ship canal aquatic nuisance species dispersal barrier. In: Chapman DC, Hoff MH (eds) *Invasive Asian carps in North America*. American Fisheries Society Special Publication 74. Bethesda, MD, pp. 121–137

Murphy EA, Jackson PR (2013) Hydraulic and water-quality data collection for the investigation of Great Lakes tributaries for Asian carp spawning and egg-transport suitability: US Geological Survey Scientific Investigations Report 2013-5106. <http://pubs.usgs.gov/sir/2013/5106/>. Accessed 11 Nov 2014

Noatch MR, Suski CD (2012) Non-physical barriers to deter fish movements. *Environ Rev* 20:71–82

Pegg MA, Chick JH (2004) Aquatic nuisance species: an evaluation of barriers for preventing the spread of bighead and silver carp to the Great Lakes. Final report for the Illinois-Indiana Sea Grant A/SE (ANS)-01-01. Illinois-Indiana Sea Grant, Urbana, IL

Popper AN, Carlson TJ (1998) Application of sound and other stimuli to control fish behavior. *Trans Am Fish Soc* 127:673–707

Popper AN, Hastings MC (2009) The effects of human-generated sound on fish integrative. *Zoology* 4:43–52

- Rankin CH, Abrams T, Barry RJ, Bhatnagar S, Clayton DF, Colombo J, Coppola G, Geyer MA, Glanzman DL, Marsland S, McSweeney FK, Wilson DA, Wu C, Thompson RF (2008) Habituation revisited: an updated and revised description of the behavioral characteristics of habituation. *Neurobiol Learn Mem* 92:135–138
- Ross QE, Dunning DJ, Thorne R, Menezes JK, Tiller GW, Watson JK (1993) Response of alewives to high-frequency sound at a power plant intake on Lake Ontario. *N Am J Fish Manag* 13(2):291–303. doi:10.1577/1548-8675(1993)013<0291:ROATHF>2.3.CO;2
- Ruebush BC, Sass GG, Chick JH, Stafford JD (2012) In-situ tests of sound-bubble-strobe light barrier technologies to prevent range expansions of Asian carp. *Aquat Invasions* 7(1):37–48
- Sampson SJ, Chick JH, Pegg MA (2009) Diet overlap among two Asian carp and three native fishes in backwater lakes on the Illinois and Mississippi rivers. *Biol Invasions* 11:483–496
- Sass GG, Cook TR, Irons KS, McClelland MA, Michaels NN, O'Hara ETM, Stroub MR (2010) A mark-recapture population estimate for invasive silver carp (*Hypophthalmichthys molitrix*) in the La Grange Reach, Illinois River. *Biol Invasions* 12:433–436
- Schilt CR (2007) Developing fish passage and protection at hydropower dams. *Appl Anim Behav Sci* 104(4):295–325
- Scholik AR, Yan HY (2001) Effects of underwater noise on auditory sensitivity of a cyprinid fish. *Hear Res* 152:17–24
- Scholik AR, Yan HY (2002a) The effects of noise on the auditory sensitivity of the bluegill sunfish, *Lepomis macrochirus*. *Comp Biochem Physiol A* 133:43–52
- Scholik AR, Yan HY (2002b) Effects of boat engine noise on the auditory sensitivity of the fathead minnow, *Pimephales promelas*. *Environ Biol Fishes* 63:203–209
- Schrank SJ, Guy CS, Fairchild JF (2003) Competitive interactions between age-0 bighead carp and paddlefish. *Trans Am Fish Soc* 132:1222–1228
- Sloan JL, Mensinger AF (2013) Acoustical conditioning and retention in the common carp (*Cyprinus carpio*). *J Great Lakes Res* 39:507–512
- Taylor RM, Pegg MA, Chick JH (2005) Response of bighead carp to a bioacoustic behavioural fish guidance system. *Fish Manag Ecol* 12:283–286
- Thompson RF, Spencer WA (1966) Habituation: a model phenomenon for the study of neuronal substrates of behavior. *Psychol Rev* 73:16–43
- Voellmy IK, Purser J, Flynn D, Kennedy P, Simpson SD, Radford AN (2014) Acoustic noise reduces foraging success in two sympatric fish species via different mechanisms. *Anim Behav* 89:191–198
- Whitfield AK, Becker A (2014) Impacts of recreational motorboats on fishes: a review. *Mar Pollut Bull* 83:24–31
- Willis DJ, Hoyer MV, Canfield DE, Lindberg WJ (2002) Training grass carp to respond to sound for potential lake management uses. *N Am J Fish Manag* 22:208–212
- Zielinski DP, Voller VR, Svendsen JC, Hondzo M, Mensinger AF, Sorensen P (2014) Laboratory experiments demonstrate that bubble curtains can effectively inhibit movement of common carp. *Ecol Eng* 67:95–103