An ensonified bubble curtain blocks 4 species of invasive carp in a laboratory flume but also deters other fish, while sound alone is less effective overall and does not target carp

Jane Rose Feely
University of Minnesota Twin Cities: University of Minnesota
Peter Sorensen (✉ soren003@umn.edu)
University of Minnesota https://orcid.org/0000-0003-0321-1279

Research Article

Keywords: Bioacoustic Fish Fence, BAFF, carp, native fish, grass carp, silver carp

Posted Date: September 20th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-799849/v1

An ensonified bubble curtain blocks 4 species of invasive carp in a laboratory flume but also deters other fish, while sound alone is less effective overall and does not target carp

Jane R. Feely and Peter W. Sorensen*
Department of Fisheries, Wildlife and Conservation Biology
University of Minnesota
2003 Upper Buford Circle
St. Paul, MN 55108, USA

Abstract Four species of invasive carp from Asia are advancing up the Mississippi River through its locks and dams and threatening to damage to its ecosystems. It has been hypothesized that sensory stimuli could be projected into locks to block the movement of these carp. Sound has garnered attention because carp are hearing specialists, so they might be targetable. A recent study demonstrated that when a broadband cyclic sound was projected into an air curtain to create an ensonified bubble curtain (EBC), it was especially effective at blocking bighead and common carp and less effective at blocking a native species that lacked hearing specializations, while sound alone was generally less effective. However, whether an EBC might be similarly and uniquely effective at blocking all species of carp, and what its effects might be on other fishes in general, has not yet been addressed. To answer these questions, this study examined the responses of 10 species of fishes including 4 carps, 2 native hearing specialists, and 4 native non-specialists in a darkened laboratory flume while either a cyclic sound was played on its own or projected into an air curtain. The EBC blocked all 4 carps 92-97% of the time without habituation, but 5 native fish were also partially blocked. In contrast, sound alone only blocked 2 carps and affected the other fishes in ways not related to their hearing abilities. An EBC appears well suited to blocking carp invasions, especially if native fish movement is a secondary concern.

Keywords Bioacoustic Fish Fence; BAFF; carp; native fish; grass carp; silver carp

*corresponding author; soren003@umn.edu

Introduction

In the 1970's, four species of carp from Asia were introduced into sewage and aquaculture ponds in the southern United States from which they escaped into the Mississippi River (Kolar et al. 2007; Chapman and Hoff 2011; Reeves 2019). These species joined the common carp (*Cyprinus carpio)* which had been introduced from Europe a century before and now dominates many lake and river ecosystems worldwide (Sorensen and Bajer 2011). The "Asian" carps are currently breeding and moving away from their site of introduction, threatening ecosystems in the upper reaches and tributaries of the Mississippi River as well as the Laurentian Great Lakes (ACRCC 2021). In most regions, the silver carp (*Hypophthalmichthys molitrix*) is of greatest concern because it is a highly efficient planktivore (Dong and Li 1994; Claus and Sorensen 2019) and jumps when startled (Stell et al. 2020). Its congener, the bighead carp (*H. nobilis*), is also considered a serious threat because it often grows to a large size (~40 kg; Kolar et al. 2007) and hybridizes with silver carp (Lamer et al. 2010). In addition to the bigheaded carps (i.e. the silver and bighead carps), concerns are growing about the grass carp (*Ctenopharyngodon idella*), which feeds on plants and is now breeding in some tributaries of Lake Erie (Cudmore and Mandrak 2004; Embke et al. 2016). Further, in the southern United States, the black carp (*Mylopharyngodon piceus*) threatens its mollusks (Nico and Jelks 2011). Finally, the common carp remains a concern because although well established, management efforts continue to remove it from waterbodies which managers do not wish them to re-invade (Sorensen and Bajer 2011). All of these carps exhibit migratory behaviors (deGrandcahamp et al. 2008; Harris et al. 2021; Banet et al. 2021) which, in the Mississippi River and its tributaries, results in their swimming through locks and dams to invade upstream habitats. Accordingly, locks and dams are being considered as pinch-points in rivers to block invasive carps by performing various actions including adding carp deterrent systems (ACRCC 2021; Zielinski and Sorensen 2021).

An especially promising option to stop the invasion of carp is to place deterrent systems in the navigation locks of locks and dams, especially locks and dams with spillway gates that rarely open and are thus not routinely passable so fish must pass through their locks (Zielinski et al. 2018; Zielinski and Sorensen 2021). Several types of deterrent systems are being considered for use in locks (Noatch and Suski 2012), but those which use nonphysical, or sensory stimuli, are favored. This is because nonphysical systems are relatively simpler and less expensive to install and run, do not pose a hazard to human health, and have the potential to target particular species because different fish species have different sensory capabilities (Fay and Tavolga 2012). Sound is of special interest because it is relatively easy to project and carp, like other ostariophysan fishes, have an exceptional sense of hearing because they possess a type of hearing specialization known as Weberian ossicles (Popper and Carlson 1998). A Weberian apparatus can extend the hearing range of fish up to ~1000 hz and increase their sensitivity by several fold (Popper and Carlson 1998; Putland and Mensinger 2019). While the effects of various sounds have been tested on about a dozen species of fish and found to have promise, a wide range of deterrence efficiencies have also been described; however, these tests have used a variety of testing apparatuses, experimental protocols, and sound signals, so conclusions about their true potential remain elusive (Zielinski and Sorensen 2017; Murchy et al. 2016; Putland and Mensinger 2019). Nevertheless, habituation, the phenomenon in which animals learn to ignore biologically-irrelevant stimuli and become less responsive to them with repeated exposure, has emerged as a concern (Zielinski and Sorensen 2017; Dennis and Sorensen 2020a). In sum, it remains an open question whether fish with hearing specializations including carps are more deterred by sound than species that lack specializations and why.

Because of the variability and often low level of responsiveness of fish to sound, studies are now testing sound in conjunction with other sensory stimuli to produce multi-modal cues that take advantage of all of their properties. One of the best studied of these are ensonified bubble curtains (EBCs), a type of stimulus in which sound is projected into an air bubble stream (i.e. air curtain) to focus and enhance sound fields while often causing its bubbles to resonate (Brevik and Kristiansen 2002; Leighton 2012; Dennis et al. 2019). In addition, bubble curtains can be aversive in their own right because they have their own acoustic, physical, and visual properties which can be felt and heard by fish acoustico-lateralis system as well as visualized (Zielinski et al. 2014; Zielinski and Sorensen 2016). A commercial version of an EBC is available and known as a bioacoustic fish fence (BAFF) (https://www.fgs.world) and has been tested a few times with some success. Welton et al. (2002) found that young, downstream-migrating Atlantic salmon (*Salmo salar)* were deterred by a BAFF by 66-79% in a small stream with the highest efficiencies being observed at night. A similar finding without a day-night effect was noted for downstream-migrating Chinook salmon smolts (*Oncorhynchus tshawytscha)* in a large river, although this BAFF was illuminated and no day-night effect was noted (Perry et al. 2014). In a raceway test, Taylor et al. (2005) found that bighead carp were repelled up to 95% of the time by a BAFF but no other fish was tested, nor was sound alone. Later, in a field test, a variety of fishes (including some carps) were captured and transplanted downstream of an illuminated BAFF and it was seen to reduce the upstream recapture of many species, including silver carp, suggesting this system can work in the field, but not how well, or why (Ruebush et al. 2012). Finally, in a laboratory test of an EBC, we found that common carp and bighead carp were nearly completely blocked by an EBC in a darkened lab flume (blockage efficiencies of 97% and 99% respectively) while largemouth bass (*Micropterus salmoides),* which lack hearing specializations, were blocked to a lesser (86%) extent (Dennis et al. 2019). We also found that an EBC worked more effectively than sound or air alone and that a cyclic broadband sound was especially effective. In sum, while these studies suggest that EBCs have promise to block carp and might even be able to target them, this type of stimulus has only been tested on a few species including two carps so conclusions about its broad applicability for field implementation cannot be drawn.

The overarching goal of this study was to determine if EBCs are a better option to control invasive carps than sound alone and if either option can target carps without significantly affecting native fishes. We asked two questions. First, does a cyclic broadband sound effectively block all four species of carp without affecting other fishes including native hearing specialists? Second, does this sound block carps more effectively than sound alone, and if so, what effects might it have on native fishes, including hearing specialists? To answer these questions, we tested the responses of 4 species of invasive carp, as well as 2 native fish species with hearing specializations and 4 without hearing specializations, to sound alone and an EBC in the darkened laboratory flume with protocols we have used previously (Dennis et al. 2019; Dennis and Sorensen 2020b).

Materials and methods

Experimental Design

Experiments proceed in a stepwise fashion, following established approaches (Dennis et al 2019; Dennis and Sorensen 2020b). First, we selected native species of interest as well as species of invasive carp that we could obtain from local hatcheries (see below). Second, we brought these fish into the laboratory where they were held in large aquaria (see below). Third, these fish were then tested following established protocols (Dennis et al. 2019) in a 8-m darkened laboratory flume as groups of 10 to one of three stimuli: 1) no stimulus ("no-treatment control" to determine their basal level of activity); 2) a cyclic sound (the same sound tested by Dennis et al. 2019; see below); or 3) this cyclic sound coupled with air to create an EBC (also the same as Dennis et al. 2019; see below). After a 1-h pre-test/acclimation period, these groups of fish were tested 8 times (each testing period was considered a trial), each of which had two sets of 6-min periods, a 6-min pre-test with no stimulus, followed by a 6-min test period with a stimulus. Trials were separated by a 10-min period with no stimulus to permit recovery. The flume was designed so a stimulus could be played on either side with side being selected at random by coin-toss for each experimental trial. Each experiment took a total of 238 min. Fish position was recorded during the pre-test and test-periods (test number) using overhead cameras (confirming crossing if/as necessary using underwater cameras), then analyzed by quantifying the number of times fish crossed the midline where the deterrent system was located (i.e., passage rate) for each pre-test or test period. Because we had a disease problem with our bighead carp, we used the data collected by Dennis et al. (2019) for this species although it was re-analyzed as our analysis differed slightly. Fish were only tested once so all fish were naive and we could address habituation with clarity.

Fish

In addition to the four species of carp that we could obtain from local hatcheries, we selected a variety of 6 native fishes based on availability, taxonomic variety, ecology, and whether or not they had hearing specializations (Table 1). Fish were sexually immature and ranged in size from about 90-200 mm in total length (TL). Channel catfish (*Ictalurus punctatus*) and lake sturgeon (*Ascipneser fulvescens*) were obtained from the Genoa National Fish Hatchery (Genoa, WI, USA) while bluegill sunfish, (*Lepomis macrochirus*), largemouth bass, golden shiners

(*Notemigonus crysoleucas*), common carp, rainbow trout (*Oncorhynchus mykiss*), grass carp, bighead carp, and silver carp were obtained from Osage Catfisheries (Osage Beach, MO, USA). All fish were shipped to the University of Minnesota and placed into inflow-through 1000L circular tanks prior to testing for at least 3 months supplied with well water on a 16:8 L:D photoperiod. Bluegill sunfish, channel catfish, largemouth bass, golden shiners, common carp, rainbow trout, and grass carp were fed 2.5 mm floating pellets (Skretting USA, Tooele, UT, USA). Silver carp and bighead carp were fed a mixture of Spirulina and Chlorella algae (Claus and Sorensen 2017; Nuts.com, NJ, USA). Lake sturgeon were fed brine shrimp (Hikari, Japan). Procedures were approved by the University of Minnesota Institutional Animal Care and Use Committee (Protocol: 1712-35381A) and all necessary federal and state permits were obtained.

Laboratory Flume

Experiments were performed in the same custom-built indoor elliptical flume (8 m long x 1 m wide channel, 1.0 m wall height) employed by Dennis et al. (2019) who provides a detailed description so only an overview is provided here for context. Briefly, the flume was constructed of fiberglass and its floor and walls (inside and out) lined with concrete pavers with foam pads to reduce sound reverberation. Sound/air sources which were positioned on its bottom at the mid-line of each of its long sides. The flume was located in a dark and quiet room and illuminated with 6 overhead infrared illumination systems (840 nm, < 1-lux; VT-IR1, Vitek, Valencia, CA). Low-light cameras were also positioned overhead so fish position could be observed at a remote location. Several underwater cameras were also placed in the flume so that crossings through the bubble curtain could be confirmed when needed. Well water (18ºC) was supplied to the flume until 1-h before the experiments started, when it was turned off except for the bighead carp trials for which a slow flow was maintained as we found they stopped swimming in stagnant water. Water depth was maintained at 0.3 m.

Stimuli

We used the same speakers, sound, and EBC set-up as that employed by Dennis et al (2019) who provides detailed descriptions of all three so only an overview is provided here for context. Briefly, the sound system was comprised of two sets of two speakers (FGS MkII 15-100; Fish Guidance System Ltd.; Southampton, UK), which were positioned equidistant from each other at the center of each of the long sides of the flume alongside two fine porous pipes (AD100T; Pentair AES; Apopka, FL). For EBC experiments the porous pipes were supplied with air at a rate of 1.2 L s^{-1} to create a fine bubble stream via blowers located in another room while sound settings were left as is. Our test sound contained frequencies between 20-2000 hz which cycled (Sound 7, Fish Guidance Systems) and was played at a volume to create a sound field of ~150-160 db at 1000 hz (ref 1 μPa) at the source (Fig. 1; see Dennis et al. 2019 for detail). Sound pressure and particle acceleration levels for both the sound and EBC were mapped using a C15 hydrophone (Cetacean Research, Seattle, WA) as well as an accelerometer (TASCAM US-12mkII; TEAC, Montebello, CA). Dennis et al. (2019) provide initial descriptions of this sound and the EBC including spectrograms and elaborate here by showing sound maps for sound pressure (SPL_{RMS}) at three selected frequencies within the carps' hearing range: 500-600hz, 1000-1100hz, and 1500-1600hz. These maps appear to show much sharper sound pressure gradients near the stimulus for the EBC than sound alone, especially for the higher frequencies, but that maximum sound pressures were similar (Fig. 1).

Statistical Analysis

Similar to Dennis et al. (2019) and Dennis and Sorensen (2020a), we used a step-wise approach to analyze our results which was based on generalized linear mixed models (GLMM). Ten models were used in total, one for each species. This approach used custom-built matrices to facilitate comparisons between species and their responses to stimuli and was more powerful and direct than a 3-way ANOVA (Dr. G. Oelhert, Statistical Consulting Center, University of Minnesota< Minneapolis, MN). In particular, these matrices allowed us to directly compare passage rates between control and test conditions for each experiment (species) as well as to calculate overall blockage efficiencies. Once we had determined whether responses to stimuli were significant, we then examined habitation using ANOVAs, before next examining differences between stimuli, species and then groups of species (ex. the carps). These steps are outlined below.

For our first step, we examined changes in passage rates using a custom design matrix for each set of experiments written in R and entered into each GLMM. In each GLMM, "fish group number" (test group) was used as a random effect to account for repeated measurements taken from that group of fish. Passage rate data for the pre-test and test periods were transformed to fit a Poisson distribution because these are count data. Assumptions of normality for each GLMM (e.g. that residuals are randomly and normally distributed) were checked visually using a plot of the deviance residuals versus fitted values to test for random distribution of residuals, while over-dispersion was tested by examining the variance of the residuals (McCullagh and Nelder 1989). If the variance of the residuals was greater than 2, we corrected for this hyper-variability by dividing our test statistic by the square root of the dispersion parameter (McCullagh and Nelder 1989) and calculating new p-values for each comparison in that GLMM (this was only necessary for silver and bighead carp). Raw passage rate counts were used as the response variable in the GLMM because our fish moved as individuals in darkness (i.e. fish were not observed to be schooling) and initial evaluations showed that all passage rates were described well by log-linear fits (Tables S1- S10). To determine whether each particular stimulus altered the passage rate of each species, we used a GLMM to compare the log-linear passage rates calculated for each control experiment for that species (N=160 control periods) with the matched log-linear passage rate calculated for when the stimulus was being tested (N = 80 test periods) ($P<0.05$). In addition, if significance was observed, we compared individual test values with their control values using the GLMM while correcting for multiple comparisons using Bonferroni function ($p < 0.05$). Finally, mean blockage efficiencies for each species and stimulus were calculated by dividing each test's calculated passage rate for each experiment by the calculated mean passage rate noted during the matched no-treatment control experiment, subtracting the resulting value from 1, and then multiplying that by 100 to get a percent. Mean blockage efficiencies were then calculated.

For our second step, we tested for changes in passage rate (habituation) over time for each experiment (species). To accomplish this, we subtracted the each test passage rate value from its matched pre-test value in experiment, divided that by the pre-test value and multiplied by 100 to derive a set of 8 passage rates for each experiment. Trends in these values were then evaluated using a separate 1-way repeated measures ANOVA (SAS Institute Inc., Cary, NC, USA) for each species and stimulus type, with trial number (1-8) being the main effect, and fish group number (1-10) as a random effect. If a decrease was described ($p < 0.05$), habituation was noted.

Next, for our third step, we determined whether coupling sound with air to make an EBC made it more effective. Mean blockage efficiencies were calculated for each species and stimulus-type, and these values compared by performing a series of Bonferroni-corrected z-tests ($p < 0.05$, $n = 10$). For a fourth step, we sought to determine which fish species were most responsive to each stimulus. To accomplish this, we performed two series of Bonferroni-corrected z-tests ($p < 0.05$, corrected for multiple comparisons). The first compared the blockage efficiencies of sound among the ten tested species ($N = 45$ comparisons), and the second compared the blockage efficiencies of sound coupled with air among the ten tested species ($N = 45$ comparisons). Finally, to determine if hearing ability (specializations) affected fish responsiveness, mean blockage efficiencies were compiled by fish type (i.e. carp, native hearing specialists, native non-hearing specialists) for sound alone and the EBC, and then compared using paired t-tests. These a priori analyses were performed using JMP Pro 13. (SAS Institute Inc., Cary NC, USA) with Bonferroni corrections ($P < 0.05$).

Results

Does a cyclic broadband sound effectively block all four species of carp without affecting other fishes, including native hearing specialists?

No-treatment control experiments showed that fish passage rates for all 10 species were relatively constant (Fig. 2, 3) and described by log-linear relationships (Supplemental Tables S1-S10). GLMM analysis next showed that the passage rates of all 10 species were affected by sound ($p<0.05$), with 9 species showing a decrease and channel catfish showing an increase (Figs. 2, 3; Table 2, 3). Habitation was noted in three species: the largemouth bass, silver carp, and grass carp (29 - 42% decreases in blockage rate with time; $p<0.05$; Table 2). The overall mean blockage efficiency for all fish was only 44 ± 37% (mean ± SD).

Examining the carps, we noted a high level of variability in the efficacy of sound at blocking the 4 carp species (Fig. 4). While bighead carp and common carp were both effectively blocked by sound (86 ± 48%, 83 ± 27% respectively) and without habituation (Figs. 2B, 2H; Table 3), silver and grass carp were only weakly affected (31 ± 12%; 21 ± 9% respectively) with habituation being noted in both instances ($p<0.05$) (Figs. 2E, 2K; Table 3). Silver carp and grass carp were blocked less than the bighead and common carp ($p<0.05$), which also did not differ from each other (Table 2), but to the same extent as largemouth bass, a native non-hearing specialist (see below). Taken as whole, the carp were not more affected by sound more than any other group of fish including native hearing non-specialists ($p>0.05$; Table 4).

Responses of native hearing specialists also varied between species. Thus, while golden shiners were blocked moderately effectively (77 ± 27%) and without habituation (Fig. 2N; Table 2), channel catfish were strongly attracted ($p<0.05$; Fig. 3B), also without habituation ($p>0.05$; Table 2). Native hearing specialists were not affected by sound more than non-hearing specialists when considered as a group ($p>0.05$; Table 4)

Finally, responses of native non-hearing specialists were found to be moderate and less variable and not to differ from each other. Thus, while bluegill sunfish were blocked with moderately effectively by sound alone (60 ± 24%; Fig. 3H) without habituation, so were lake sturgeon (47 ± 24%; Fig. 3N), rainbow trout (45 ± 27%; Fig. 3K), and largemouth bass (34 ± 27%) which also showed habituation ($p<0.05$) (Fig. 3E; Table 2).

Does the cyclic sound block carps more effectively that sound alone and if so, what effects might it have on native fishes, including hearing specialists?

GLMM analysis for each of the 10 species exposed to the EBC showed that the passage rates of all 10 species decreased dramatically when exposed to this multi-modal stimulus ($p<0.05$; Figs. 2, 3). Notably, habituation was not observed for any species (Table 4). Taken as a whole, the mean blockage efficiency for all 10 species to the EBC was 82 ± 23%, nearly twice that of the sound. Increases in blockage were noted for all 10 species, which on average differed by 11% ($P<0.05$) (Fig. 4).

Mean blockage efficiencies for all 4 carp were consistently high (94 ± 29%) for the EBC and while the silver carp was blocked more efficiently than the other 3 carp species ($p<0.05$; Table 3), the difference was small (2%) and the other carp species did not differ from each other ($p>0.05$). While silver carp were blocked 97 ± 36% of the time (Fig. 2F), bighead carp were blocked 92% ± 42% of the time (Fig. 2C), grass carp 95 ± 24% of the time (Fig. 2L), and common carp 95 ± 42% of the time (Fig. 2I). When the carp were analyzed as a group the carps were blocked more than the native non-hearing specialists ($p<0.05$%), but not the native hearing specialists ($p>0.05$) (Table 5).

Both of the native hearing specialists were also blocked more efficiently by the EBC than sound alone (36% increase; $p<0.05$). While golden shiners were blocked with high efficiency by sound (89 ± 27%; $p<0.05$) and without habituation (Fig. 2P; Table 2), channel catfish were weakly repelled ($P<0.05$; Fig. 3C) without habituation ($p>0.05$; Table 3). Notably, this species had been attracted by the sound alone (41%, see above).

Finally, responses of the native non-hearing specialists were relatively strong ($P<0.05$) and did not differ from each other ($p>0.05$), or golden shiners, a hearing specialist (Table 3). Thus, while bluegill sunfish were moderately blocked ($p<0.05$) by the EBC (83% ± 30%) without habituation (Fig. 3I), so were lake sturgeon (84% ± 39%) (Fig. 3P), rainbow trout (81% ± 39%) (Fig. 3P), and largemouth bass (88 ±48%) (Fig. 3I, Table 3).

Discussion

Our laboratory study clearly demonstrated that ensonified bubble curtains (EBCs) are a highly effective way to block the movement of 4 species of invasive carp presently found in North America. However, while the effects of an EBC on all 4 tested carps were substantial (92 - 97% blockage), and carp did not habituate to it, we also found that the EBC partially blocked many native fishes, including some lacking hearing specializations. In contrast, the sound projected into the EBC was much less effective when tested on its own for all 10 fish species, especially the silver and grass carp, which were blocked less than 50% of the time and habituated. Remarkably, no relationship was noted between whether species had hearing specializations or not and how strongly they were responded by the sound alone. In contrast, responses to the EBC were seen to be weakly carp-specific. We conclude that EBCs offer genuine and unique promise to block invasive carps in rivers, including the highly invasive grass and silver carps, although their effects on the movement of native fishes will need to be addressed.

Our most important finding was that the EBC we tested functions as a singularly effective fish deterrent for fish, and carp in particular. All 4 species of the carp we tested, including the silver and grass carp, were nearly completely blocked and without habituation. However, although carps as a group were more affected the EBC, 5 of the other 6 native species we tested were also strongly effected with blockage efficiencies in the 81-89% range. Thus, although the EBC did not target carps very effectively, it did show promise in that regard. We expect the EBC to have similar effects on other carp including the black carp. Importantly, our results appear replicable; the results of this study are nearly identical to those previously described for both the common carp (95% vs 99%, a hearing specialist, and largemouth bass, a non-hearing specialist (88% vs. 87%) (Dennis et al. 2019). The reasons for the EBC's high level of overall efficacy likely relate to its multi-modal nature with sound playing an important role (see below). Our finding of extremely high blockage efficiencies are also similar to those noted by a commercial BAFF tests for carp. Taylor et al. (2005) noted an approximate 90% block of bighead carp in a hatchery raceway. Additionally, Ruebush et al. (2012) noted similarly high blockage rates (seemingly over 95%) for wild transplanted silver carp in a small creek using an illuminated BAFF under natural conditions although they, like us, noted that a number of native species were also seemingly affected. In any case, the EBCs appear to present new opportunities for reliably controlling carp passage.

Our second most important finding was that the sound we tested, and which Dennis et al. (2019) had previous found more effective than another broadband sound, was consistently less effective than the EBC for all 10 species of fish while having little effect on two carps and being plagued by habituation. Especially notable was the fact the nether silver nor grass carps were strongly affected by sound alone. The blockage efficiencies we noted for common carp and largemouth bass were also very similar to those seen previously for sound (83% vs 79%; 34% vs 50%; Dennis et al. 2019). Indeed, our study may be the first study to show such a high level of repeatability, suggesting that the high level of variation between species is biologically relevant. Especially intriguing was our observation that the channel catfish was strongly attracted to the sound, perhaps reflecting the fact that this species uses a stridulatory sound that might resemble the cyclic sound to communicate (Fine et al. 1995). Also interesting and relevant was the fact that silver and grass carp quickly habituated to this sound after showing a few strong responses. In both cases, we were testing small, young fish that were very active; perhaps these fish were innately more motivated to stay active to find food than to avoid a sound of little apparent significance. Notably, we were able to repeat the silver carp results on a small scale with few unused fish (Fig S1) and all fish were healthy. Although we were the first to test responses of grass carp to sound, others have tested much older/ larger silver carp. While Vetter et al. (2015) noted consistent aversion in a well-lit tank that may have permitted visual learning, Zielinski and Sorensen (2017) tested silver carp in darkness and observed rapid habitation as noted here. Habituation, the tendency of animals to learn to ignore biologically irrelevant stimuli (Rankin et al. 2007) once again appears to be a challenge when testing sound alone (Dennis and Sorensen 2020b), at least to the synthetic sounds being employed. We do not believe that there is anything unusual about the broadband cyclic sound we tested because while Dennis et al. (2019) showed it to be more effective than the broadband outboard-motor sound, the difference was not great or qualitatively different. Together, the results of ours studies and others (Putland and Messinger 2019) describe responses to sound varying by species and testing scenario, calling into question the value of sound on its own to block carps in rivers.

It is interesting and important to speculate why the EBC is so potent because understanding its actions might lead to more effective and/or better targeted EBCs. By previously showing that the effects of an EBC on three species of fish were greater than elicited by either sound or air alone, Dennis et al. (2019) provided compelling evidence that the EBC is multi-modal. The weak relationship we saw between EBC potency and fish hearing ability in our experiment (at least for carp), also argues that factors in addition to sound pressure are important. Likely, particle motion, which is perceived by all fish with otoliths, plays a role in the actions of the EBC because sturgeon, which are insensitive to pressure component of sound, showed surprisingly robust responses to the EBC in our study. However, while the specific characteristics of the sound used in an EBC may be important, it does not appear to be critical or enabling because Dennis et al. (2019) showed the cyclic sound to be only ~10% more effective than the outboard motor sound, and quantitatively no different. Likely an EBC is effective because it produces a range of sensory fields that are detected by multiple sensory systems as fish encounter the sharp but complex sound pressure, particle motion, and tactile cues associated near EBCs (Leighton 2002; Leighton et al. 2004; Dennis et al. 2019). We speculate that this combination of sensory cues may be perceived as novel and distinctive by fish which then seek to avoid it because it is stress-inducing. Avoidance is easily achievable because walls of bubbles and the sensory fields associated with them can followed (Dominico 1982; Leighton et al. 2004; Dennis et al. 2019). Sound does not act in such a complex manner. The dynamic, turbulent nature of bubble curtains may also reduce habituation. In this way, fish that hear well (i.e. detect sound pressure via hearing specializations) such as carp, will be especially deterred (unless the sound is actually innately relevant to them), but those that do not hear it will still detect the EBC and avoid it. The carps may be strongly deterred because they share a common set of sensory systems and neurological/ cognitive processes in addition to hearing. If true, then the efficacy of EBC might be increased and targeted by varying the nature of the bubble systems (bubble size, flow and structure) and how sound pressure is coupled to it to drive resonance, as well as by adding other stimuli to match sensory perception in carps. Introducing visual cues (see below) into air curtains might be another possible option, as seen at some commercial BAFFs (Perry et al. 2014). These possibilities will require additional study that should pair high-resolution measurement of all sensory fields associated with EBCs, fish sensory physiology, and fish behavior, both in the laboratory and natural world.

Our study had some significant strengths and a few weaknesses. We believe it is the largest study of its kind to test acoustic stimuli as deterrents on fish, having tested 10 species to two stimuli and using over 3000 individuals. We tested only naive (and healthy) fish, although all were immature and unmotivated. Importantly, our findings both replicate and compliment those of Dennis at al. (2019), and support field observations with a BAFF (see below). Nevertheless, like all laboratory studies our study has its limitations. In particular, we only tested small sample of the many taxa of fish found in the Mississippi River and only one type of hearing specialization (i.e. the Webarian apparatus in Ostariphysans). Further, we only tested one water depth and set of lighting conditions (darkness) and some experiment suggest that BAFF are more effective in the day (Welton et al. 2002). We also did not test the effects of water flow which would alter EBC structure and acoustics in rivers. More field tests of EBCs that include more variables and both carps as well as native fishes are needed to expand on Ruebush et al. (2012)'s pioneering work. Light should be included because carp are deterred by it and when used to illuminate air curtains, it proves additional orientational cues (Dennis and Sorensen 2020b). These tests should consider measuring sensory fields in detail and evaluating how fish approach and hopefully avoid these fields, or some combination thereof. Efforts probably need to consider effects on migrating native fish and also how possible concerns might be addressed by running BAFFs using different types of bubble systems at times that target carp migrations, or perhaps using traps (or fish ladders) in combination with the air curtain so that native fish can be captured and moved upstream while carp are removed. The economic and environmental damage being wrought by invasive carps and the value of maintaining biodiversity argue that these possibilities are well worth exploring (ACRCC 2021).

In conclusion, the results of this study, taken together with those of Dennis et al. (2019) in the laboratory and others in the field (Ruebush et al. 2012), demonstrate that EBCs have great and singular promise to stop invasive carps while carrying some risk of disrupting the movement of native fishes. However, based on the present results, sound on its own would appear to little promise at stopping all species of carps, especially grass and silver carps, or effectively targeting any group. Field and laboratory studies of EBCs are urgently needed to elucidate their actions on wild fish while determining how they work and might be improved.

Acknowledgments

We thank the Minnesota Aquatic Invasive Species Research Center for helping administer the project and providing laboratory space. Dr. Andy Turnpenny provided technical support for the laboratory equipment which was leased from Fish Guidance Systems Ltd. without conditions or any expectation. Help with statistical design and analyses were provided by the University of Minnesota's Institute for Research on Statistics and its Applications (IRSA) Statistical Consulting Center. Dan Krause, Rosie Daniels, Kirsten Engseth, Kory Davis, Pheng Lor, Laura Wagner. Austin Abbott, Nicholas Jacob, and Kara Van Lerberghe provided invaluable help with fish husbandry, running experiments. Clark Dennis provided invaluable help with experimental design, protocols and data analysis.

Declarations

Funding: Funding for this project was provided by the Minnesota Environmental and Natural Resources Trust Fund as recommended by the Legislative-Citizen Commission for Minnesota Resources (LCCMR).

Conflicts of interest/ competing interests: Not applicable.

Availability of Data and Materials: Data are available from the authors upon request.

Code availability: Available from authors upon request

Author contributions. This research was conceived by Peter Sorensen who also acquired the funding and edited final drafts of the manuscript. Data collection and analysis was performed by Jane Feely who wrote the first drafts of the manuscript.

Ethics approval: Procedures were approved by the University of Minnesota Institutional Animal Care and Use Committee (Protocol: 1712-35381A).

References

Asian Carp Regional Coordinating Committee (ACRCC) (2021) Asian Carp Action Plan available at https://www.asiancarp.us/

Banet NV, Fieberg J, Sorensen PW (2021) Migration, homing and spatial ecology of common carp in interconnected lakes. Ecol Fresh Fish DOI10.1111/eff12622

Brevik I, Kristiansen O (2002) The flow in and around air-bubble plumes. Int. J. Multiph. Flow.

28:617–634.

Chapman DC, Hoff MH (2011) *Invasive Asian carps in North America*. American Fisheries Society, Bethesda, MD

Claus A, Sorensen PW (2019) Chemical cues which include amino acids mediate species-specific feeding behavior in invasive filter-feeding bigheaded carps. J. Chem Ecol, *43*:374-384.

Cudmore B, Mandrak N (2004) Biological Synopsis of Grass Carp (*Ctenopharyngodon idella*). Can Manuscript Rept Fish Aquat Sci 2705

DeGrandchamp KL, Garvey JE, Colombo RE (2008) Movement and habitat selection by invasive Asian carps in a large river. Trans Amer Fish Soc 137:45-56.

Dennis CE, Zielinski DP, Sorensen PW (2019) A complex sound coupled with an air curtain blocks invasive carp passage without habituation in a laboratory flume. Biol Invas 21:2837-2855

Dennis CE, Sorensen PW (2020a) High-intensity light blocks Bighead Carp in a laboratory flume. Manag Biol Invas 11:441-460.

Dennis CE, Sorensen PW (2020b) Common carp are initially repelled by a broadband outboard motor sound in a lock chamber but habituate rapidly. N Amer J Fish Manag 40:1499-1509.

Dominico SN (1982) Acoustic wave propagation in air-bubble curtains in water- part 1. History and theory. Geophysics 37:345-353.

Dong S and Li D (1994) Comparative studies on the feeding selectivity of silver carp *Hypophthalmichthys molitrix* and bighead carp *Aristichthys nobilis*. J Fish Biol 44:612-626.

Embke H, Kocovsky P, Richter C, Pritt J, Mayer C, Qian S (2016) First direct confirmation of grass carp spawning in a Great Lakes tributary. J Great Lakes Res 42:899-903.

Fay R, Tavolga W (2012). *Sensory biology of aquatic animals*. Springer Science & Business Media.

Fine M, McElroy D, Rafi J, King C, Loesser K, Newton S (1995) Lateralization of Pectoral stridulation sound production in the channel catfish. Physiol Behav 60:753-757.

Harris C, Brenden T, Vandergoot C, Faust M, Herbst S, Krueger C (2021) Tributary use and large-scale movements of grass carp in Lake Erie. J Great Lakes Res 47:48-58.

Kolar C, Chapman D, Courtenay W, Housel C, Williams J, Jennings D (2007) Bigheaded carps: A biological synopsis and environmental risk assessment. American Fisheries Society, Bethesda, MD

Lamer JT, Dolan CR, Petersen JL, Chick JL, Epifanio JM (2010) Introgressive hybridization between bighead and silver carp in the Mississippi and Illinois rivers. N Amer J Fish Manage 30:1452-1461.

Leighton, TG (2012). *The acoustic bubble*. Academic Press, London

Leighton, TG, Richards SD, White PR (2004) Trapped within a “wall of sound.” Accoust Bull 29:24-29.

Lu Z, Popper A, Fay R (1996) Behavioral detection of acoustic particle motion by a teleost fish (*Astronotus ocellatus*): sensitivity and directionality. J Comp Physiol 179:227-233.

McCullagh P, Nelder J. 1989. Binary data. Generalized linear models: 98-148. Springer US.

Murchy K, Vetter B, Brey M, Amberg J, Gaikowski M, Mensinger A (2016). Not all carp are created equal: Impacts of broadband sound on common carp swimming behavior. In

Proceedings of Meetings on Acoustics 4ENAL (Vol. 27, No. 1, p. 010032). Acoustical Society of America.

Nico L, Jelks H (2011). The Black Carp in North America: An Update. American Fisheries Society Symposium 74:89-104.

Noatch M, Suski C (2012) Non-physical barriers to deter fish movements. Env Rev 20: 1-12.

Perry RW, Romine JG, Adams NS, Blake AR, Burau JR, Johnston SV, Liedtke TL (2014) Using a non-physical behavioural barrier to alter migration routing of juvenile chinook salmon in the Sacramento–San Joaquin River delta. River Res Appl 30:192-203.

Popper AN, Carlson T (1998) Application of sound and other stimuli to control fish behavior. Trans Amer Fish Soc 127:673-707.

Putland R, Mensinger A (2019) Acoustic deterrents to manage fish populations. Rev Fish Biol Fish 29:789-807.

Rankin CT, Abrams R, Barry S, Bhatnagar D, Clayton J, Colombo G, Coppola M, Geyer D, Glanzman S, Marsland F, McSweeney F (2009). Habituation revisited: an updated and revisedcdescription of the behavioral characteristics of habituation. Neurobiol Learn Mem 92:135–138.

Reeves A (2019) *Overrun: Dispatches from the Asian Carp Crisis*. Toronto: ECW Press.

Ruebush B, Sass G, Chick J, Stafford J (2012). In-situ tests of sound-bubble-strobe light barrier technologies to prevent range expansions of Asian carp. Aquat Invasions 7:37-48.

Smith ME, Kane AS, Popper AN (2004). Noise-induced stress response and hearing loss in goldfish (*Carassius auratus*). J Exp Biol 207:427-435.

Stell E, Hoover J, Fuller L, Parsons G (2019) Analyzing leap characteristics and water escape velocities of Silver Carp using in situ video analysis. N Amer J

Fish Manag 40:163-174.

Sorensen PW, Bajer PB (2011) Common carp. In: Biological Invasions, No. 3. Berkley and Los Angeles editors: University of California Press.

Taylor RM, Pegg MA, Chick JH (2005) Response of a bighead carp to a bioacoustics behavioural fish guidance system. Fish Manag Ecol 12:283-286.

Vetter BJ, Cupp AR, Fredricks KT, Gaikowski MP, Mensinger AF (2015). Acoustical deterrence of silver carp (*Hypophthalmichthys molitrix*). J. Biol Invas 17:3383-3392.

Welton JS, Beaumont WRC, Clarke RT (2002) The efficacy of air, sound, and acoustic bubble screens in deflecting Atlantic salmon, *Salmo salar* L., smolts in the River Frome, UK. Fish Manag Ecol 9:11-18.

Zielinski DP, Sorensen PW (2016) Field test of a bubble curtain deterrent system for common carp. Fish Manag Ecol 22:181-184.

Zielinski DP, Sorensen PW (2017) Silver, bighead, and common carp orient to acoustic particle motion when avoiding a complex sound. PLOS One.12:e0180110

Zielinski DP, Sorensen PW (2021) Numeric simulation demonstrates that the upstream movement of invasive bigheaded carp can be blocked at sets of Mississippi River locks-and-dams using a combination of optimized spillway gate operations, lock deterrents, and carp removal. Fishes 6, 10. https://doi.org/10.3390/fishes6020010

Zielinski DP, Voller VR, Sorensen PW (2018) A physiologically inspired agent-based approach to model upstream passage of invasive fish at a lock-and-dam. Ecol Model 382:18-32.

Zielinski DP, Voller VR, Svendsen JC, Hondzo M, Mensinger AF, Sorensen PW (2014). Laboratory experiments demonstrate that bubble curtains can effectively inhibit movement of common carp. Ecol Eng 67:95-103.

Figure legends

Fig. 1 Schematic drawing of an overhead view of the elliptical laboratory flume used by this study and by Dennis et al. (2019) as well as Dennis and Sorensen (2020b). Pairs of speakers were placed in mid-channel along with an air injection system. Panels A-F to the right show plan views of sound pressure (RMS) levels in dB (ref 1 μPa) at different frequency ranges for sound alone (A, C, F) and the ensonified bubble curtain (EBC) (B, D. G) (see text for details).

Fig. 2 Mean passage rates ± standard deviation (SD) (i.e. number of passages per 6-min pre-test or test period with stimulus) of 5 species of fish with hearing specializations (4 carps and 1 native hearing specialist) during control conditions (no stimulus), sound only, and sound coupled with air as an ensonified bubble curtain (EBC) across time. Test number is indicated on the x-axis and differences between individual pre- and test passage rates are shown by an asterisk ($p<0.05$; see text): (A). Bighead carp - control; (B) Bighead carp - sound only; (C). Bighead carp - EBC; (D). Silver carp - control; (E) Silver carp - sound only; (F). Silver carp - EBC; (G). Common carp - control; (H) Common carp - sound only; (I) Common carp - EBC; (J). Grass carp - control; (K) Grass carp - sound only; (L). Grass carp, - EBC; (M). Golden shiners- control; (N) Golden shiners - sound only; (O). Golden shiners – EBC. Note that scale is different fro silver and grass carp as they were more active.

Fig. 3 Mean passage rates ± standard deviation (SD) (i.e. number of passages per 6-min pre-test or test period with stimulus) of 1 species of native hearing specialist and 4 native non-hearing specialists during control conditions (no stimulus), when tested with sound alone, and sound coupled with air as an ensonified bubble curtain (EBC) across time. Test number is indicated on the x-axis and differences between individual pre- and test passage rates are shown by an asterisk ($p<0.05$; see text): (A). Channel catfish - control; (B) Channel catfish - sound only; (C). Channel catfish - EBC; (D). Largemouth bass - control; (E) Largemouth bass - sound only; (F). Largemouth bass - EBC; (G). Bluegill sunfish - control; (H) Bluegill sunfish - sound only; (I) Bluegill sunfish - EBC; (J). Rainbow trout- control; (K) Rainbow trout - sound only; (L). Rainbow trout - EBC; (M). Lake sturgeon - control; (N) Lake sturgeon - sound only; (O). Lake sturgeon – EBC.

Fig. 4 Mean blockage efficiencies ± standard deviation (SD) of 10 species of fish to sound alone (light bars) or an ensonified bubble curtain (EBC, dark bars). Rates for each species were compared with each other (see Tables 2 and 3) and between sound and EBC (see text). Differences for the latter ($p<0.05$) are noted with an asterisk.

Table 1 Species tested, their taxonomic group, origin, size, and whether they possess hearing specializations.

Fish Species	Family	Native or Non-native	Length (mean ± SD) cm	Weight (mean ± SD) g	Hearing Specialization (Yes or No)
Bighead carp (BC) (*Hypophthalmichthys nobilis*)	Cyprinidae	Non-native	142 ± 15	33.06 ± 8.48	Yes
Silver carp (SC) (*Hypophthalmichthys molitrix)*	Cyprinidae	Non-native	85 ± 11	5.58 ± 1.55	Yes
Common carp (CC) (*Cyprinus carpio*)	Cyprinidae	Non-native	110 ± 19	20.22 ± 10.59	Yes
Grass carp (GC) (*Ctenopharyngodon idella)*	Cyprinidae	Non-native	133 ± 18	24.34 ± 9.78	Yes
Golden shiners (GS) (*Notemigonus crysoleucas)*	Cyprinidae	Native	88 ± 10	6.52 ± 3.18	Yes
Channel catfish (CH) (*Ictalurus punctatus)*	Ictaluridae	Native	138 ± 19	23.62 ± 8.89	Yes
Largemouth bass (LB) (*Micropterus salmoides)*	Centarchidae	Native	124 ± 23	24.76 ± 13.54	No
Bluegill sunfish (BS) (*Lepomis macrochirus)*	Centrarchidae	Native	106 ± 15	20.75 ± 10.19	No
Rainbow trout (RT) (*Oncorhynchus mykiss)*	Salmonidae	Native	130 ± 13	24.50 ± 5.24	No
Lake sturgeon (LS) (*Acipenser fulvescens)*	Acipenseridae	Native	162 ± 18	12.75 ± 3.14	No

Table 2. Effects of sound alone on the passage rates of 10 species of fish. Species, mean passage rates for the no-treatment control and test periods (calculated from individual trials), mean blockage efficiency (from GLMM), habituation, comparisons between the blockage efficiencies between the 10 species (p<0.05). Mean ± Standard Deviation (SD).

Species	Mean Passage Rate Control	Mean Passage Rate Sound	Mean Blockage Efficiency	Habituation Measured (Yes or No)	Blocked More Than:	Blocked Less Than:
Bighead Carp (BC)	14 ± 8	2 ± 2*	86 ± 48%	No	GC, SC, CH, LS, RT, LB, BS	N/A
Silver Carp (SC)	30 ± 20	35 ± 21*	31 ± 12%	Yes	CH	BC, CC, GS, BS
Common Carp (CC)	16 ± 9	3 ± 4*	83 ± 27%	No	GC, SC, CH, LS, RT, LB, BS	N/A
Grass Carp (GC)	57 ± 14	46 ± 20*	21 ± 9%	Yes	CH	BC, CC, GS, LS, RT, LB, BS
Golden Shiners (GS)	10 ± 5	4 ± 3*	77 ± 27%	No	GC, SC, CH, LS, RT, LB, BS	N/A
Channel Catfish (CC)	11 ± 5	19 ± 7^{+}	-41 ± 15%	No	N/A	BC, CC, GC, SC, GS, LS, RT, LB, BS
Largemouth Bass (LB)	11 ± 10	3 ± 3*	34 ± 27%	Yes	CH	BC, CC, GS, BS
Bluegill Sunfish (BS)	8 ± 3	3 ± 2*	60 ± 24%	No	GC, SC, CH, LB	BC, CC, GS
Rainbow Trout (RT)	7 ± 5	5 ± 4*	45 ± 27%	No	GC, CH	BC, CC, GS
Lake Sturgeon (LS)	8 ± 6	5 ± 4*	47 ± 24%	No	GC, SC, CH	BC, CC, GS

*decrease in passage rate vs. control rate measured by GLMM (P<0.05); + significant increase; N/A= no affect

Table 3 Effects of the ensonified bubble curtain (EBC) on passage rates of 10 species of fish. Species, mean passage rates for no-treatment control and test periods (calculated from individual trials), mean blockage efficiency (from GLMM), habituation, comparisons between the blockage efficiencies of the 10 species ($p<0.05$). Means ± Standard Deviation (SD).

Species	Mean Passage Rate Control	Mean Passage Rate EBC	Mean Blockage Efficiency	Habituation? (Yes or No)	More Effective Than Sound?	Blocked More Than:	Blocked less Than:
Bighead Carp (BC)	14 ± 8	1 ± 0.6*	92 ± 53%	No	Yes	CH, RT	SC
Silver Carp (SC)	30 ± 20	1 ± 3*	97 ± 36%	No	Yes	BC, CC, GS, BS, LS, RT, LB, GC, CH	N/A
Common Carp (CC)	16 ± 9	0.9 ± 1*	95 ± 42%	No	Yes	CH, GS, LS, RT, LB, BS	SC
Grass Carp (GC)	57 ± 14	3 ± 3*	95 ± 24%	No	Yes	CH, GS, LS, RT, LB, BS	SC
Golden Shiners (GS)	10 ± 5	1 ± 0.5*	89 ± 36%	No	Yes	CH	CC, GC, SC
Channel Catfish (CT)	11 ± 5	10 ± 3*	19 ± 18%	No	Yes	N/A	BC, CC, GC, BS, LS, RT, LB,SC, GC
Largemouth Bass (LB)	11 ± 10	0.8 ± 1*	88 ± 48%	No	Yes	CH	CC, GC, GC
Bluegill Sunfish (BS	8 ± 3	2 ± 2*	83 ± 30%	No	Yes	CH	CC, GC, SC
Rainbow Trout (RT)	7 ± 5	1 ± 2*	81 ± 39%	No	Yes	CH	CC, GC, SC
Lake Sturgeon (LS)	8 ± 6	1 ± 1*	84 ± 39%	No	Yes	CH	CC, GC, SC

* decrease in passage rate versus no-treatment control measured by GLMM ($P<0.05$); N/A= not affected

Table 4. Effects of sound alone on different groups of fish (carp, native hearing specialists, native non-hearing specialists). No differences (P>0.05) were noted.

Groups Being Compared	Mean Blockage Efficiency	Difference (Prob > |t|)
Carp vs. Native hearing specialists	55 ± 34% vs. 18 ± 83%	0.6405
Carp vs. Native non-hearing specialists	55 ± 34% vs. 46 ± 11%	0.6552
Carp + Native hearing specialists vs. Native non-hearing specialists	43 ± 49% vs. 46±10.7%	0.8670

Table 5. Effects of the ensonified bubble curtain (EBC) on different groups of fish (carp, native hearing specialists, native non-hearing specialists). Difference is noted at $p<0.05$.

Groups Being Compared	Mean Blockage Efficiencies	Difference (Prob > |t|)
Carp vs. Native hearing specialists	95 ± 29% vs. 54 ± 42%	0.4516
Carp vs. Native Non-hearing specialists	95 ± 31% vs. 84 ± 84%	0.0015*
Carp + Native hearing specialists vs. Native non-hearing specialists	81 ± 31% vs. 84 ± 3%	0.8304

*$P < 0.05$

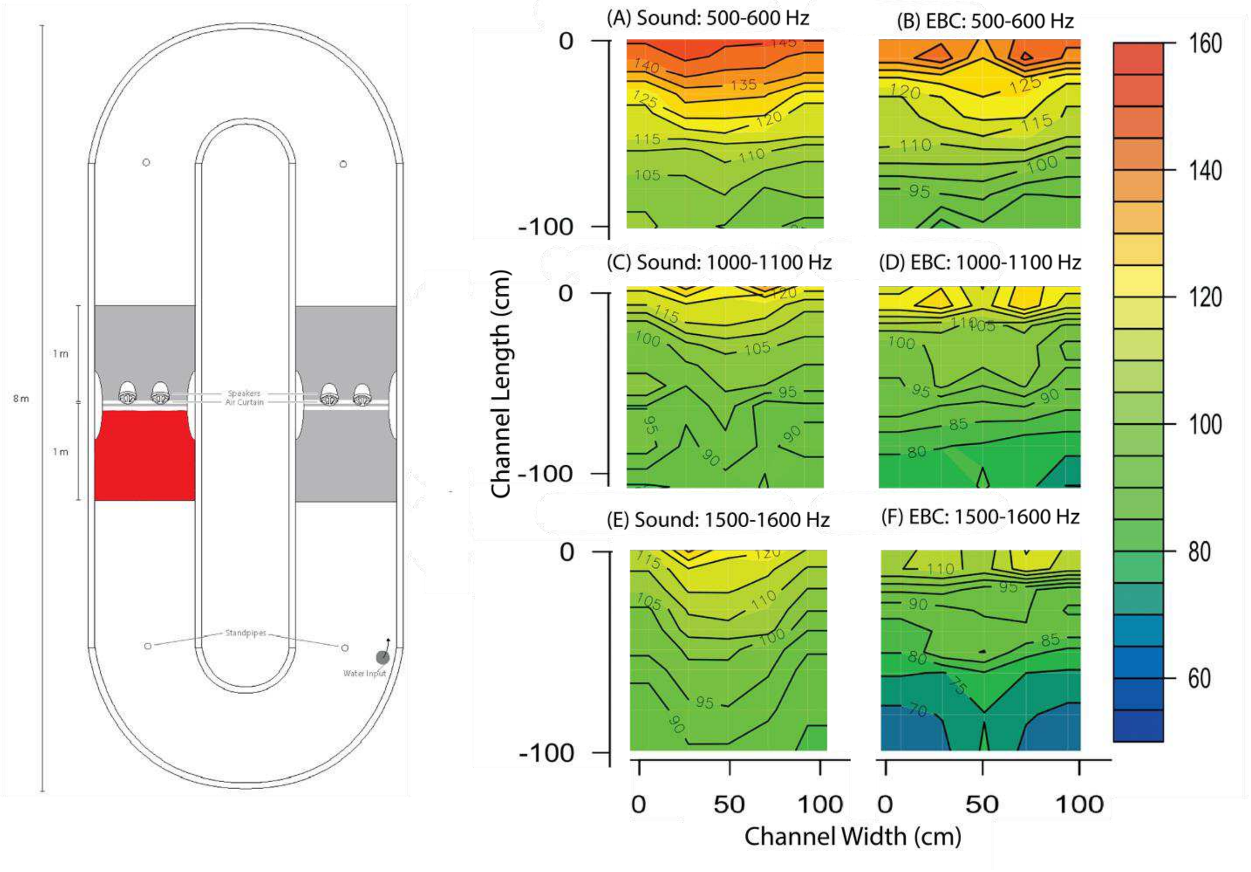

8 m
1 m
1 m
Speakers
Air Curtain
Standpipes
Water Input
(A) Sound: 500-600 Hz
(B) EBC: 500-600 Hz
(C) Sound: 1000-1100 Hz
(D) EBC: 1000-1100 Hz
(E) Sound: 1500-1600 Hz
(F) EBC: 1500-1600 Hz
Channel Length (cm)
0
-100
Channel Width (cm)
0
50
100
160
140
120
100
80
60

Fig 1

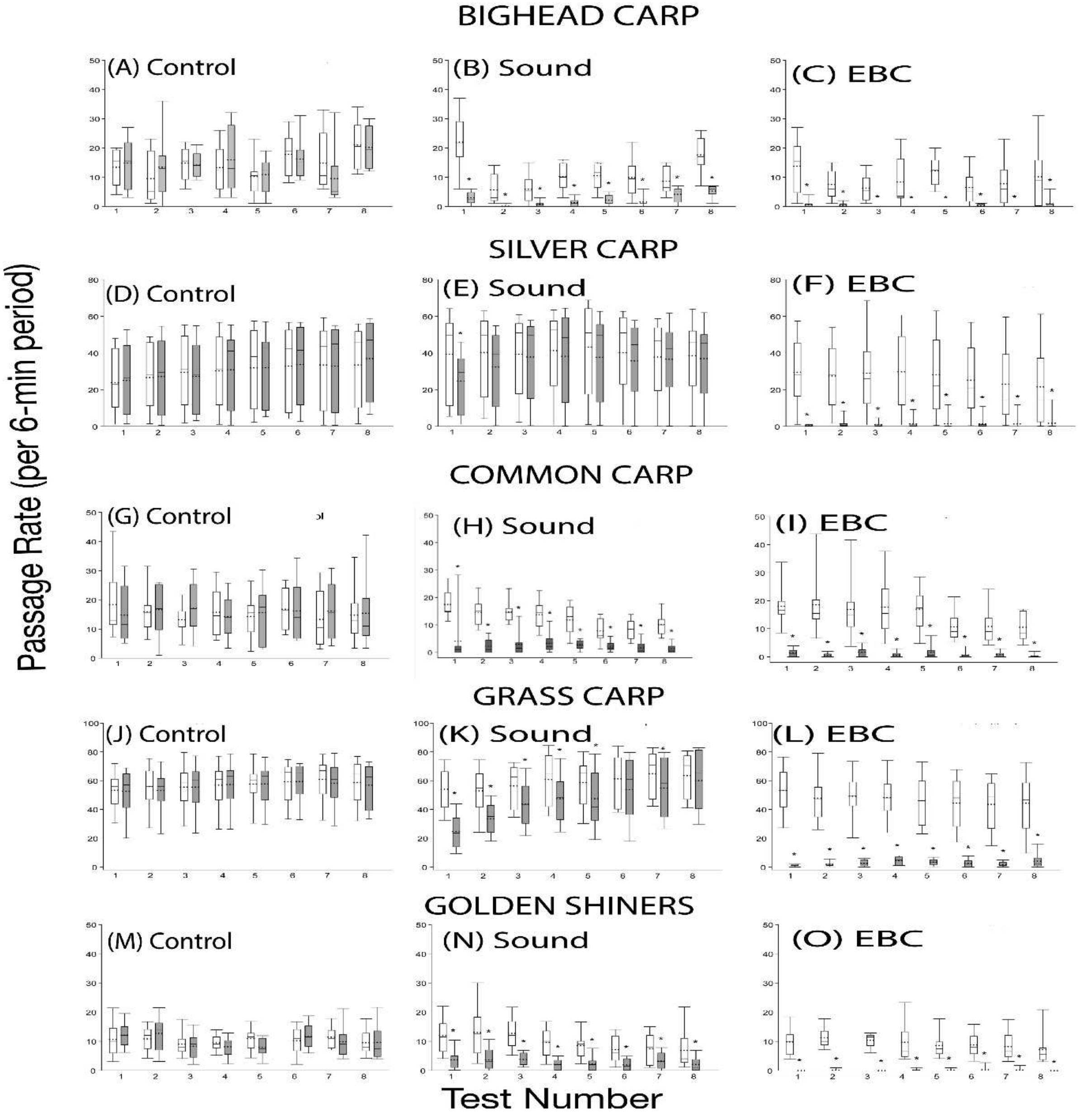
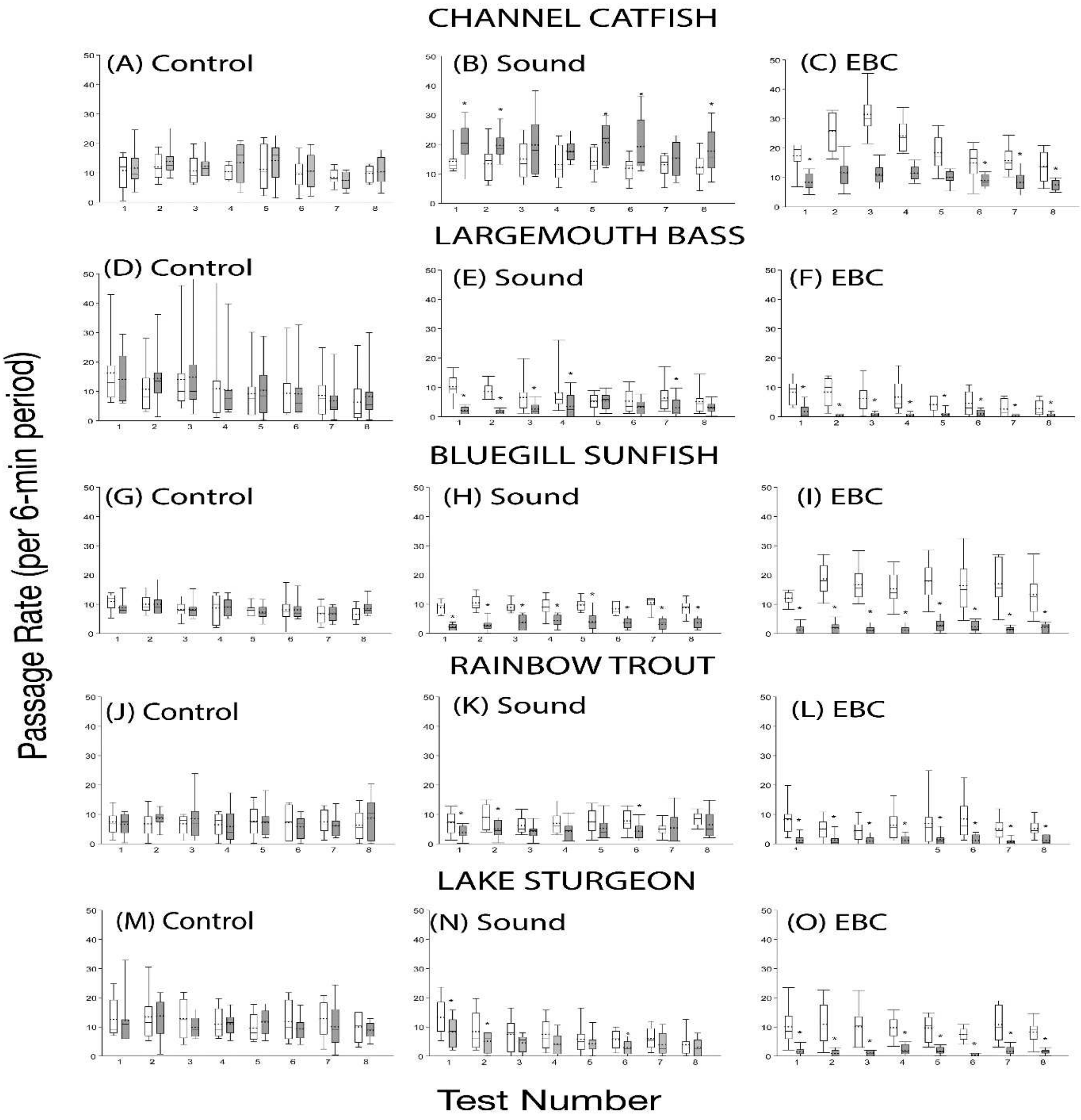
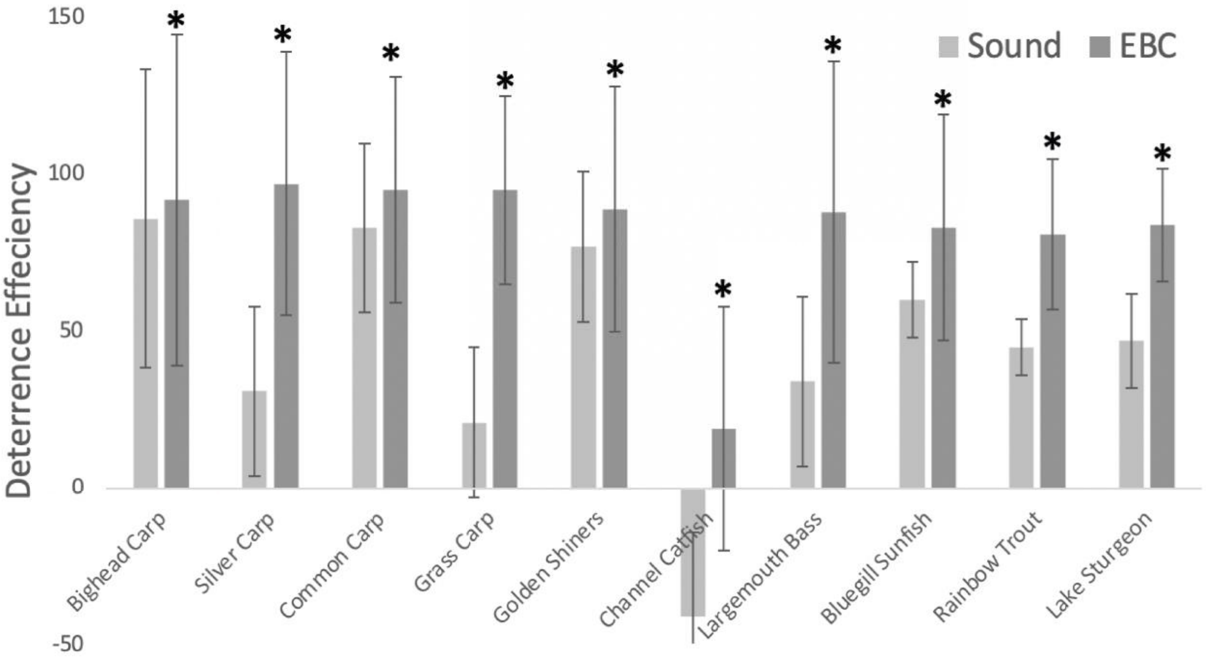

BIGHEAD CARP
(A) Control
(B) Sound
(C) EBC
SILVER CARP
(D) Control
(E) Sound
(F) EBC
COMMON CARP
(G) Control
(H) Sound
(I) EBC
GRASS CARP
(J) Control
(K) Sound
(L) EBC
GOLDEN SHINERS
(M) Control
(N) Sound
(O) EBC
Passage Rate (per 6-min period)
Test Number

Fig. 2


CHANNEL CATFISH
(A) Control
(B) Sound
(C) EBC
LARGEMOUTH BASS
(D) Control
(E) Sound
(F) EBC
BLUEGILL SUNFISH
(G) Control
(H) Sound
(I) EBC
RAINBOW TROUT
(J) Control
(K) Sound
(L) EBC
LAKE STURGEON
(M) Control
(N) Sound
(O) EBC
Passage Rate (per 6-min period)
Test Number
0
10
20
30
40
50
1
2
3
4
5
6
7
8
*



150
100
50
0
-50
Deterrence Effeciency
Sound
EBC
*
Bighead Carp
Silver Carp
Common Carp
Grass Carp
Golden Shiners
Channel Catfish
Largemouth Bass
Bluegill Sunfish
Rainbow Trout
Lake Sturgeon

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- FeelyandSorensenAugust82021Supplementaryinfo.pdf