The effects of noise on the auditory sensitivity of the bluegill sunfish, *Lepomis macrochirus*<sup>†</sup>

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Abstract

As concerns about the effects of underwater anthropogenic noises on the auditory function of organisms increases, it is imperative to assess if all organisms are equally affected by the same noise source. Consequently, auditory capabilities of an organism need to be evaluated and compared interspecifically. Teleost fishes provide excellent models to examine these issues due to their diversity of hearing capabilities. Broadly, fishes can be categorized as hearing specialists (broad hearing frequency range with low auditory thresholds) or hearing generalists (narrower frequency range with higher auditory thresholds). The goal of this study was to examine the immediate effects of white noise exposure (0.3–2.0 kHz, 142 dB re: 1 μPa) and recovery after exposure (1–6 days) on a hearing generalist fish, bluegill sunfish (*Lepomis macrochirus*). Noise exposure resulted in only a slight, but not statistically significant, elevation in auditory threshold compared to fish not exposed to noise. In combination with results from our previous studies examining effects of noise on a hearing specialist fish, the fathead minnow (*Pimephales promelas*), this study provides evidence supporting the hypothesis that fish’s auditory thresholds can be differentially affected by noise exposure.

Keywords: Auditory brainstem response; Centrarchidae; Cyprinidae; Hearing generalist fish; Hearing specialist fish; Threshold shift; Underwater noise; White noise

1. Introduction

Recently, there has been heightened concern about the effects of underwater noise on freshwater and marine organisms. This is a result of the increasing amount of noise in the underwater acoustic environment associated with anthropogenic sources (Richardson et al., 1995; Gordon and Moscrop, 1996). Though sounds generated from boats and ships are considered the main sources, there are a vast number of anthropogenic noise sources, including underwater explosions, sonars, air guns, dredges, ocean science studies, hydroelectric dams, fishing equipment with acoustic deterrent devices, and noises associated with oil and gas production (Richardson et al., 1995; Richardson and Würsig, 1997). Though most of these sources generate noise only as a by-product, many produce it intentionally. Regardless, there are an expansive number of potential noise sources an aquatic or marine organism may encounter in its environment.

Despite the amount of noise in the underwater environment, there have been few studies directly addressing the auditory effects of noise on aquatic organisms. Many behavioral studies have been conducted, but they may not give a comprehensive...
picture of the effects of noise exposure on the physiology of the auditory system. For example, Myrberg (1990) reported that many fish species have been found in the vicinity of offshore petroleum drilling platforms, which are considered quite noisy. He brings forth a pertinent question to consider: are the fishes assembled in this area because they are deafened and their ability to acoustically assess their surroundings is severely compromised or does the noise simply not affect their auditory system? Furthermore, fishes, as well as marine mammals, may react differently to noises, either by fleeing the area, remaining stationary, or even become attracted to the noise source (Richardson and Würsig, 1997). Richardson and Würsig (1997) remark that because an organism may endure noise exposure does not necessarily mean that the noise itself does not have any adverse effects.

In addition, it is erroneous to think that all organisms would be equally affected by a noise source. This has already been demonstrated by examining behavioral effects of noise on marine mammals in terms of sex, age, general activity, time of year, and habitat (Richardson and Würsig, 1997). Though, one factor that is often neglected is the organism’s general hearing ability. Different organisms have variation in their auditory capabilities, in terms of not only hearing frequency ranges but also auditory threshold levels. It can, therefore, be hypothesized that hearing ability also plays an important role in the response an organism has to a noise source. The end result is that there are multitudes of different noise sources in the underwater environment along with an abundance of different organisms that can potentially be affected, and very little information so far addressing the effects of noise on hearing thresholds of species with different auditory capacities.

The first step in addressing these issues is finding appropriate animal models, and fishes provide a means of better understanding the effects of noise on hearing. What makes fish such suitable models, is that there is no one universal ‘fish ear’ due to the vast amount of structural and physiological diversity among the inner ear and its peripheral structures, which causes great degrees of differences in hearing abilities among fishes (Platt and Popper, 1981; Schellart and Popper, 1992; Popper and Fay, 1993, 1999). Therefore, fishes offer the unique opportunity to examine a variety of hearing mechanisms and their responses to noise exposure.

Essentially, a fish’s sensitivity to sound depends on the presence of a gasbladder (von Frisch, 1938; Coombs and Popper, 1979; Yan et al., 2000) or gas-holding auditory ancillary structures: supra-branchial chambers (Schneider, 1941; Ladich and Yan, 1998; Yan, 1998), otic gasbladders (von Frisch, 1938; Stipetic, 1939; Yan and Curtsinger, 2000; Fletcher and Crawford, 2001), otic bullae (Blaxter et al., 1979; Denton et al., 1979; Gray and Denton, 1979; Blaxter et al., 1981) and the degree of coupling or proximity these structures have with the fish’s inner ear. One common type of accessory structure is the Weberian apparatus, of otophysan fishes (i.e. minnows and catfish), which are modified vertebrae connecting the anterior portion of the gasbladder to the inner ear (Evans, 1925). This accessory apparatus acts to transduce the pressure component of sound, associated with the vibration of the gasbladder, into particle motion which directly stimulates the sensory epithelium of the inner ear (Finneran and Hastings, 2000). Fishes with direct coupling devices or auditory ancillary structures are referred to as hearing specialists because they hear over a wide frequency range with lower auditory threshold. Conversely, fishes without these coupling devices and that hear over a narrower frequency range with higher auditory thresholds are referred to as hearing generalists (Tavolga and Wodinsky, 1963; Popper and Fay, 1993, 1999). Consequently, along with the anatomical diversity associated with the fish’s auditory structures, there is a correlation with anatomy and hearing capabilities (see review in Platt and Popper, 1981). Therefore, it has been speculated that noise may not affect every fish equally due to the diversity of the fish ear itself (Hastings et al., 1996).

There have been several previous studies examining the physical effects and morphological damage associated with intense noise exposure on the inner ear of fishes (Enger 1981; Hastings, 1995; Hastings et al., 1996). Two of the species examined were hearing generalists, the oscar (Astronotus ocellatus) and cod (Gadus morhua), though the cod has wider hearing range than most hearing generalist species (Sand and Karlson, 1986; Astrup and Møhl, 1993, 1998), while one was a hearing specialist, the goldfish (Carassius auratus). All the studies detected mechanical injury to the sensory hair cells after exposure to intense sound
ranging from 180 to 204 dB (re: 1 μPa), but damage was limited in the oscar (A. ocellatus) compared to that seen in the goldfish (C. auratus). Hastings et al. (1996) attributed this difference in hair cell damage to variation in overall hearing ability (hearing generalists vs. specialists) between the two species. All of these studies only addressed morphological effects of noise exposure, not auditory threshold effects.

Studies examining auditory effects of noise on fishes, have been limited and have, so far only examined hearing specialist fishes. Popper and Clarke (1976) investigated the effects of pure tone noise stimuli (149 dB, re: 1 μPa) on the goldfish. Our previous study (Scholik and Yan, 2001), examined the effects of white noise on auditory sensitivity of the fathead minnow (Pimephales promelas) and indicated that the effects of intense white noise exposure (142 dB, re: 1 μPa) was frequency and exposure duration dependent. The next issue of interest was to examine if white noise exposure yielded similar results in a fish without enhanced hearing mechanisms, a hearing generalist fish.

The purpose of this study was to examine how intense noise affected the auditory sensitivity of a hearing generalist fish, the bluegill sunfish (Lepomis macrochirus). The bluegill sunfish (Family Centrarchidae) is considered a relatively important sport fish in the North America. Its natural habitats ranges from southern Canada to northern Mexico, including the midwest and eastern regions of the USA (Trautman, 1981; Helfman et al., 1997). Due to its wide range of distribution in various types of aquatic habitats, the bluegill has the potential to be exposed to a variety of acoustic environments. Hence, it is a useful model for the present study.

We hypothesized that since hearing generalists, like bluegill sunfish, lack Weberian ossicles or ancillary structures to enhance hearing sensitivity, and thus have an auditory range that is narrower in frequency bandwidth with higher overall auditory thresholds than hearing specialists (e.g. fathead minnows) (Scholik and Yan, 2001, 2002), their hearing thresholds should be less affected by noise. Specifically, the two main objectives of our study were to (1) examine the immediate effects of noise exposure (0.3–2.0 kHz, 142 dB re: 1 μPa) using various exposure duration (2, 4, 8 and 24 h), and to (2) assess recovery (1–6 days) of auditory thresholds after exposure to 24 h of white noise using the auditory brainstem response (ABR) recording technique. In addition, we were interested in comparing the results from the present study, for a hearing generalist, to those we previously obtained (Scholik and Yan, 2001) for a hearing specialist fish. This comparison allows us to investigate if the impacts of noise exposure can be equally applied to fishes of different hearing abilities.

2. Materials and methods

2.1. Subjects

Bluegill sunfish (L. macrochirus) used for this study (72.3–105.4 mm total length (TL); 5.0–20.6 g wet body weight) were obtained from a local fish hatchery (Newtown, OH). In general, hatchery ponds are relatively ‘quiet’ environments (75–80 dB re: 1 μPa; H.Y. Yan unpublished survey data), though actual measurements for these specific ponds could not be obtained. These fish were considered juveniles, approximately 6–7 months old during the experimental procedure. While in the laboratory, fish were housed in a 320 gallon circular tub with a filtration system (average SPL: <115 dB, re: 1 μPa, 0.3–2.0 kHz) at 25 ±1 °C, under 14L:10D light cycle, and fed commercially prepared pellets (Hikari). The animal use protocol used in this study was approved by the University of Kentucky Institutional Animal Care and Use Committee (00217L2001).

2.2. White noise exposure

Fish were exposed to a white noise source with a bandwidth of 0.3–2.0 kHz at 142 dB (re: 1 μPa), which was generated using Tucker–Davis Technologies (TDT) SigGen™ software. White noise is defined as a noise source that has a flat power spectrum as a result of all frequencies being presented at an identical average intensity or pressure (Yost, 2000). The bandwidth of the noise was particularly chosen to encompass the entire auditory range of the bluegill sunfish, excluding those frequencies below 0.3 kHz, where lateral line inputs could come become an extraneous factor (Münz, 1985, 1989; Popper and Fay, 1993; Coombs and Montgomery, 1999).

Once generated, the noise was then fed through a DA1 digital–analog converter, a PA4 programmable attenuator, and a power amplifier (QSC...
A mesh sling, which was attached to a glass rod suspended 1 m above a plastic tub, where the fish were housed during the noise exposure duration.

Noise exposure of subjects, as a group, occurred in a plastic tub (38×24.5×14.5 cm³) with 5.5-cm depth of water. The fish were free to swim about the tub during the exposure, but a fine mesh screen was placed over the tub to prevent them from jumping outside. The plastic tub sat upon a vibration-free air table (Kinetic Systems, model 1201) inside a soundproof chamber (2×3×2 m², Industrial Acoustics Company Inc.).

The use of white noise as an acoustic stimulus is to represent a generic sound that a fish might encounter in its environment. Since most underwater anthropogenic noise sources are not composed of pure tones (reviewed in Urick, 1983; Greene and Moore, 1995; Gordon and Moscrop, 1996; Richardson and Würsig, 1997), the use of white noise allows one to better understand the auditory effects of noise exposure over a wider frequency range and is more realistic than creating an artificial noise of a single discrete frequency.

2.3. Auditory brainstem response (ABR) recording technique

Hearing thresholds were obtained using the auditory brainstem response (ABR) recording technique, which is defined as an electrophysiological far-field recording of synchronous neural activity of the eighth cranial nerve and associated auditory brainstem nuclei in response to an acoustic stimulus (Yost, 2000). This recording technique and its application on the auditory physiology of fishes are described in great detail by several papers including Kenyon et al. (1998), Ladich and Yan (1998), Yan (1998), Yan et al. (2000), Yan and Curtsinger, (2000) and Scholik and Yan (2001, 2002). Thus, only a synopsis of the technique is given for this study.

In order to reduce myogenic noise, a fish first was sedated with an injection of Flaxedil (gallamine triethiodide, Sigma Chemical Co., St. Louis, MO) at a dosage ranging from 20 to 70 μl (5 mg/15 ml: 0.3 mg/ml). Then it was restrained in a mesh sling, which was attached to a glass rod that was fixed in a micromanipulator (M330, World Precision Instruments, Sarasota, FL). The restrained fish was immersed in a plastic tub (34.3 cm×47.0 cm×17.1 cm), so that the nape of the head was approximately 1 mm above the water surface. Once sedated and immersed, a respiration pipette was placed in the fish’s mouth and a recording electrode, along midline of skull at region of medulla, and a reference electrode, approximately 5 mm anterior of reference electrode, (Teflon-insulated silver wire, 0.25 mm in diameter with 1 mm of exposed tip) were placed firmly against the head of the fish. In addition to the fish being in the tub, a hydrophone (Celesco LC-10), used to monitor the sound pressure levels (SPL) of the auditory stimuli, was placed near the head of the fish.

A Tucker–Davis Technologies modular rack system running TDT BioSig™ software was used to present sound stimuli and measure ABR waveforms. This system was controlled by an optically linked Pentium III, 350 MHz desktop computer housing a TDT board. The sound stimuli consisted of eight frequencies (0.3, 0.4, 0.5, 0.6, 0.8 1.0, 1.5 and 2.0 kHz) and were presented for 20 ms as tone bursts of the specified frequency (2000 sweeps per test) and sound pressure level. All stimuli for the ABR recording technique and those used for noise exposure, were presented using a 30-cm diameter speaker (Pioneer) mounted 1 m above the fish.

To measure auditory thresholds, the highest sound pressure level was presented first and then attenuated in 5 dB steps for all frequencies until a repeatable ABR waveform was no longer obtainable, which was determined using visual inspection of the waveform. In addition, cross-correlation coefficient (r) examination was also used to determine threshold, where any r value of <0.3 is considered below threshold (Yan, 1998; Yan et al., 2000; Yan and Curtsinger, 2000; Scholik and Yan, 2001, 2002).

2.4. Experiment 1: immediate effects of white noise exposure

To assess the immediate effects of white noise exposure, groups of bluegill sunfish (n=6) were exposed to various durations of noise, ranging from 2 to 24 h at 142 dB (re: 1 μPa). Immediately following noise exposures, thresholds were measured using the ABR recording technique. One-way ANOVAs, with multiple comparisons (Dunnett test) using SigmaStat software, were used to compare exposure duration effects against baseline fish exposure.
(those not exposed to noise) for each of the eight auditory frequencies measured.

2.5. Experiment 2: Recovery after 24 h exposure

To examine recovery of auditory sensitivity after 24 h of noise exposure, auditory thresholds were measured at 1, 2, 4 or 6 days (n=6 for each condition) following exposure. During the days following noise exposure, fish were kept in separate aquaria in an isolated room, where auditory disturbances were kept minimal (average SPL: < 103 dB re: 1 μPa, 0.3–2.0 kHz) until auditory testing could be completed. Separate one-way ANOVAs, with multiple comparisons (Dunnett test), were used to compare recovery time for each hearing frequency and day against baseline thresholds using SigmaStat software.

2.6. Comparison of audiograms

To have a more comprehensive understanding of how noise exposure impacts auditory threshold changes in a hearing generalist (e.g. bluegill sunfish, present study) and a specialist fish, data from our previous study using the fathead minnow (Scholik and Yan, 2001) are included for comparison.

3. Results

3.1. Experiment 1: immediate effects of white noise exposure

To assess the immediate effects of noise exposure duration on auditory thresholds, audiograms were measured for groups of bluegill sunfish exposed to noise for 2, 4, 8 or 24 h, with all thresholds being compared to baseline thresholds or those fish receiving no noise exposure. Fig. 1 (upper two traces) exhibits the results from 24 h of noise exposure compared to baseline fish. Though, there is a slight elevation in threshold after noise exposure, statistically out of all the eight frequencies tested, none were significantly different from the baseline fish (P > 0.05).

Table 1a includes data for the other exposure duration of 2, 4 and 8 h of noise. Again, none of the varying exposure duration yielded a statistically significant difference from the baseline group of fish (P value range: 0.08–0.74). The overall results shown in Table 1a and Fig. 1 demonstrate clearly that noise exposure, of various duration, does not significantly elevate auditory threshold at the frequencies examined.

3.2. Experiment 2: recovery after 24 h white noise exposure

Since there was a slight, although statistically nonsignificant, elevation in auditory threshold after 24 h of noise exposure, the timetable of threshold recovery was further examined. Audiograms for fish recovering from noise exposure were obtained from 1 to 6 days after exposure to 24 h of noise. Again, none of the recovery days, after noise exposure, yielded a statistical significant difference from the baseline group of fish (P value range: 0.13–0.83). Though, there is an overall trend demonstrating a decrease in auditory threshold from day 1 to 6, indicating that recovery may possibly be occurring (Table 1b).
3.3. Comparison with hearing specialist fish

Though the results from this study are notable alone, they become even more so when they are compared to our previous experiment (Scholik and Yan, 2001), in which a fathead minnow, received the same type of white noise exposure. Both groups of fishes were subjected to same duration (24 h) of noise exposure (142 dB re: 1 μPa) (as indicated by horizontal bar, solid and dashed, in Fig. 1), however, the difference in threshold shifts between the two group was very significant (Fig. 1). For the fathead minnows, five (0.3, 0.8, 1.0, 1.5, 2.0 kHz) out of eight frequencies, shown, exhibited statistically significant changes of thresholds (Fig. 1, lower two traces). On the contrary, no significant changes of threshold shifts were observed in all eight frequencies tested in the bluegill sunfish (Fig. 1, upper two traces).

The differential impacts of noise exposure on two distinct species of fish can be further demonstrated by examining changes of mean threshold in Fig. 2. For the bluegill sunfish, noise exposure yielded less than a 5-dB threshold shift for all auditory frequencies examined, and none of these changes were statistically significant from baseline thresholds. On the other hand, for the fathead minnows, all threshold shifts were larger than 5 dB. In the fish’s most sensitive hearing range (0.8–2.0 kHz), they ranged from 10 to 20 dB greater than baseline thresholds. Thus, the results in Figs. 1 and 2 indicate clearly that threshold shifts due to noise exposure are species-dependent, i.e. fathead minnows respond significantly, while bluegill sunfish do not show any significant elevation of thresholds.

![Fig. 2. Changes of mean threshold (dB) as a function of frequency after exposure to 24 h white noise (142 dB re: 1 μPa) between the bluegill sunfish and the fathead minnow (fathead minnow data are taken from Scholik and Yan, 2001). Solid triangles: threshold shift in fathead minnow. Solid circle: bluegill sunfish. Frequency range is in a log, base 10, scale.](image)

4. Discussion

The bluegill sunfish is one of the major game fishes in the eastern part of North America and has been artificially introduced into various water bodies by many state and federal agencies (Helfman et al., 1997). Such a cosmopolitan species is an ideal choice for an animal model to better understand how anthropogenic noise could impact auditory physiology. In addition, up to date, no such noise impact study on auditory physiology has been carried out using a hearing generalist species, such as the bluegill sunfish. The utilization of this species provides a unique window into

### Table 1

(a) Shown are threshold values measured immediately after white noise exposure for 2, 4, 8, and 24 h and (b) threshold values measured for 1, 2, 4, and 8 days of recovery after exposure to 24 h noise (both given with standard errors)

<table>
<thead>
<tr>
<th>Frequency (kHz)</th>
<th>Baseline</th>
<th>2 h</th>
<th>4 h</th>
<th>8 h</th>
<th>24 h</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3 kHz</td>
<td>122.9 ± 1.3</td>
<td>120.9 ± 1.6</td>
<td>124.4 ± 1.2</td>
<td>125.3 ± 1.1</td>
<td>125.0 ± 1.5</td>
</tr>
<tr>
<td>0.4 kHz</td>
<td>118.7 ± 2.0</td>
<td>121.1 ± 1.7</td>
<td>124.0 ± 2.3</td>
<td>122.7 ± 1.8</td>
<td>122.2 ± 1.2</td>
</tr>
<tr>
<td>0.5 kHz</td>
<td>122.6 ± 1.9</td>
<td>123.7 ± 1.1</td>
<td>125.0 ± 1.9</td>
<td>124.9 ± 0.9</td>
<td>123.2 ± 1.5</td>
</tr>
<tr>
<td>0.6 kHz</td>
<td>122.1 ± 2.0</td>
<td>120.0 ± 1.2</td>
<td>123.9 ± 2.5</td>
<td>125.8 ± 1.0</td>
<td>126.1 ± 1.1</td>
</tr>
<tr>
<td>0.8 kHz</td>
<td>126.5 ± 1.3</td>
<td>123.3 ± 0.9</td>
<td>125.7 ± 2.1</td>
<td>127.4 ± 1.4</td>
<td>128.2 ± 1.3</td>
</tr>
<tr>
<td>1.0 kHz</td>
<td>126.5 ± 1.6</td>
<td>124.9 ± 2.1</td>
<td>125.1 ± 1.4</td>
<td>128.2 ± 1.1</td>
<td>128.3 ± 2.0</td>
</tr>
<tr>
<td>1.5 kHz</td>
<td>132.7 ± 1.5</td>
<td>131.1 ± 2.5</td>
<td>134.2 ± 1.7</td>
<td>129.1 ± 3.3</td>
<td>136.1 ± 1.2</td>
</tr>
<tr>
<td>2.0 kHz</td>
<td>133.9 ± 1.4</td>
<td>134.3 ± 1.4</td>
<td>134.7 ± 0.9</td>
<td>133.1 ± 2.4</td>
<td>138.7 ± 1.4</td>
</tr>
</tbody>
</table>

(b) Recovery after 24 h noise

<table>
<thead>
<tr>
<th>Days</th>
<th>1 day</th>
<th>2 days</th>
<th>4 days</th>
<th>6 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3 kHz</td>
<td>124.1 ± 1.1</td>
<td>121.3 ± 1.5</td>
<td>118.8 ± 1.7</td>
<td>122.2 ± 3.0</td>
</tr>
<tr>
<td>0.4 kHz</td>
<td>123.7 ± 0.2</td>
<td>118.9 ± 1.9</td>
<td>120.6 ± 1.6</td>
<td>121.8 ± 1.3</td>
</tr>
<tr>
<td>0.5 kHz</td>
<td>126.5 ± 1.6</td>
<td>119.0 ± 1.7</td>
<td>124.6 ± 1.9</td>
<td>121.9 ± 2.8</td>
</tr>
<tr>
<td>0.6 kHz</td>
<td>125.9 ± 2.4</td>
<td>120.3 ± 1.0</td>
<td>124.4 ± 1.8</td>
<td>121.8 ± 3.3</td>
</tr>
<tr>
<td>0.8 kHz</td>
<td>125.7 ± 2.1</td>
<td>125.1 ± 1.9</td>
<td>125.2 ± 2.1</td>
<td>123.2 ± 2.5</td>
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<tr>
<td>1.0 kHz</td>
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<td>124.6 ± 2.3</td>
<td>126.8 ± 1.2</td>
<td>126.5 ± 2.1</td>
</tr>
<tr>
<td>1.5 kHz</td>
<td>129.0 ± 4.6</td>
<td>127.8 ± 1.7</td>
<td>131.9 ± 1.2</td>
<td>135.3 ± 0.9</td>
</tr>
<tr>
<td>2.0 kHz</td>
<td>137.1 ± 2.7</td>
<td>137.7 ± 1.6</td>
<td>138.6 ± 1.0</td>
<td>137.8 ± 1.9</td>
</tr>
</tbody>
</table>

All data are in dB re: 1 μPa.
examining how noise impacts the majority of fishes that are hearing generalists.

4.1. White noise exposure: immediate effects and recovery

In this study, we demonstrated that exposure to intense noise for various exposure durations (2–24 h) did not result in a statically significant elevation in auditory threshold for the eight frequencies tested (0.3–2.0 kHz). Though a slight elevation in threshold was noticeable after 24 h of exposure.

In addition, recovery after 24 h exposure was examined, up to six days after noise exposure but yielded no statistically significant results. In Table 1a,b some of the thresholds measured after noise exposure were lower than baseline thresholds. These few anomalies observed do not indicate that noise exposure decreases auditory thresholds. Instead, this can be explained by the fact that each testing condition was done using a different group of 6 fish and that pre-existing individual variations in threshold might have to be considered.

4.2. Hair cell addition with growth

As noted, the bluegill sunfish used in this experiment were juveniles, and it is a well-known phenomenon that inner ear hair cell proliferation occurs postembryonically in fishes (Corwin, 1983; Popper and Hoxter, 1984, 1990; Lombarte and Popper, 1994; Lanford et al., 1996). With this addition, the question is whether or not auditory thresholds change with hair cell proliferation.

Few studies have addressed this issue. Popper (1971) and Wysocki and Ladich (2001) both examined hearing specialist species, while Kenyon (1996) was the first to demonstrate ontogenetic changes in auditory sensitivity in hearing generalist species. Using two species of bicolor damselfish (Pomacentrus partitus and P. variabilis), he found that overall hearing ability increased with the age and size of the fish. In an addition, Yan (unpublished data) confirmed that different sizes of bluegill sunfish exhibited differences in hearing abilities. In light of these findings, future studies should examine if noise exposure could create differential impacts on distinct size and age classes of bluegill sunfish.

4.3. Differential effects of noise exposure

Taken with the results of our previous study (Scholik and Yan, 2001), we demonstrated that white noise can have differential auditory impacts on fishes. The same duration of noise exposure, 24 h, resulted in statistically significant threshold shifts in the fathead minnow, while the bluegill sunfish was minimally affected. This phenomenon can be explained when one considers the auditory capabilities of these two distinct species.

The horizontal bar (solid and dashed) in Fig. 1 indicates the noise level experienced by both bluegill sunfish and fathead minnows. For the fathead minnow, the SPL of the noise level was over 60 dB greater than threshold in the fish’s most sensitive hearing frequency range. Conversely, for the bluegill sunfish, the overall noise SPL was less than 25 dB greater than threshold in its most sensitive auditory frequency range. It is obvious that fathead minnows experienced a much more significant difference in SPL between baseline thresholds and noise exposure levels than that of the bluegill sunfish.

A point worth discussing is: did differences between baseline thresholds and noise exposure levels lead to differential responses to noise and subsequently no significant elevation in the bluegill sunfish’s auditory threshold. Yan et al. (2000) demonstrated that gasbladder deflation in a hearing specialist fish (C. auratus) resulted in a significant elevation of hearing thresholds, comparable to that of a hearing generalist species. In light of this finding, future research should be directed at deflating the gasbladder of the fathead minnow, followed by noise exposure, to investigate if changes in threshold become nonsignificant, comparable to that of bluegill sunfish after noise exposure. Additionally, experiments can be conducted providing a noise source 60 dB above hearing threshold of the bluegill sunfish to examine if the same degree of threshold elevation, similar to that of the fathead minnow, can be observed.

4.4. Ecological significance

Despite 24 h noise exposure only resulted in a statistically insignificant elevation of auditory thresholds in juvenile bluegill sunfish, one does not know what kind of detriments, if any, even a slight elevation in threshold may cause a fish in its natural daily activities. Myrberg (1981) empha-
sized the importance of the auditory system in fishes for detecting predators, prey, alarm responses, and signaling mates. In addition, hearing may be used to accurately assess the acoustic landscape (Popper and Fay, 1993, 1999). One could speculate, since the sense of hearing is so important for fishes, in terms of detecting biologically significant factors, that fishes with even a slight detriment in hearing may have a disadvantage. This is an area where further studies, addressing the relationship between diminished auditory capabilities and behavioral effects, are needed.

Even though this study strictly examined an artificially generated white noise source, these results are relevant and applicable to anthropogenic noise sources fishes may encounter in their natural environment. Recently, we used engine noise from 55 horsepower boat outboard motor (power spectrum major peak at 1.3 kHz) to assess the immediate effects of 2 h of this noise played at 142 dB (re: 1 Pa) on auditory sensitivity of the fathead minnow (Scholik and Yan, 2002). It was found that this anthropogenic noise source significantly elevated the fathead minnow’s auditory threshold in its most sensitive hearing frequency range, 1.0–2.0 kHz. Based on our previous results (Scholik and Yan, 2001, 2002) and the results of this study, it can be speculated that the same boat engine noise would affect auditory sensitivity of bluegill sunfish minimally compared to fathead minnows.

Nevertheless, in their acoustic environment, all fishes whether hearing specialists or generalists are being exposed to the same noises. Specifically, the response and auditory sensitivity of an individual fish species in a local assemblage should be taken into account when sound is intentionally used to modify behavior and prevent entrapment (reviewed in Popper and Carlson, 1998). Our results indicate that a bluegill sunfish may be minimally affected, while a fathead minnow may exhibit extensive threshold shifts when exposed to the same noise source.

This phenomenon, of differential effects of noise exposure on auditory sensitivity, may not be limited exclusively to fishes. Ketten (1992) explained, in terms of anatomy and auditory sensitivity, that the cetaceans can be divided into three main acoustic groups. Each group equates with a specific cochlear morphology and use of acoustical frequencies (i.e. infrasonic vs. ultrasonic). In light of our present study and previous findings (Scholik and Yan, 2001), it may be speculated that an underwater noise source may not effect all marine mammals equally.

4.5. Summary

The results of this study indicate that the bluegill sunfish’s auditory threshold is minimally affected by exposure to an intense noise source (142 dB re: 1 µPa), even after as much as 24 h of duration. In addition, combining the results obtained from this study and a previous study (Scholik and Yan, 2001), we provide evidence to support the hypothesis that a noise source does not affect all fishes equally. This effect is based on variation in auditory capabilities (frequency range and overall auditory threshold) of different species, which is dependent on differences in anatomical structures between inner ear and gasbladder. Furthermore, this finding emphasizes the importance of considering differences in auditory abilities of fishes when examining deleterious effects of intense noise exposure whether behaviorally or physiologically. Consequently, this should also be a concern when considering the effects of all sounds on any marine or freshwater organism.

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