Threshold of hearing for swimming Bluefin tuna (Thunnus orientalis)

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Hearing thresholds for three pairs of 1 m long Pacific bluefin tuna (Thunnus orientalis) were measured utilizing operant conditioning procedure with a food reward and a staircase psychophysical technique. Fish, swimming at 2-3 m/sec, quickly learned to approach the feed when they heard a sound. Measurements were made at the Tuna Research and Conservation Center (Stanford University) in a 9.14 m diameter, 1.65 m deep indoor cylindrical tank. The acoustic stimulus was produced by radially oriented piezoelectric line sources centered at the bottom of the tank which produced a circumferentially uniform sound field. The acoustics of the tank was thoroughly characterized for both acoustic pressure and particle motion using hydrophones and two neutrally buoyant accelerometers with response axes oriented in the radial and vertical directions. Thresholds, expressed in terms of pressure and particle acceleration were obtained at six sinusoidal frequencies between 325 Hz and 800 Hz, a range that was limited by source and tank acoustics. The lowest mean threshold for the three fish pairs, expressed in terms of acoustic pressure, was 83 dB re 1 µPa at 500 Hz. [Supported in part by ONR/CNR Challenge Grant: "Mitigation of flow noise effects by fish"]

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INTRODUCTION

All fishes have ears, and all species tested to date can hear, although there is substantial interspecific variation in hearing range and sensitivity (e.g., Fay, 1988; Popper et al., 2003). Determination of hearing range and sensitivity (thresholds), however, have rarely been conducted on free-swimming animals (e.g., Iversen, 1967, 1969). Thus, little is known about how well fishes can hear while swimming Understanding hearing while swimming is critical, however, since in order to hear well while swimming at high speed, fishes would have to have evolved methods for coping with flow noise. Understanding just how fishes hear while swimming at high speeds may be applicable to enhancing many applied technologies, such as reducing flow noise in hull mounted and towed acoustic sensor arrays.

The Pacific bluefin tuna (PBT, Thunnus orientalis) is an ideal species for investigating the ability of fish to cope with flow noise. Pacific bluefin are capable of swimming at very high speeds (perhaps up to 20 m/s) and cruise at ~8 – 10 m/s. Pacific bluefin, as most other species of tuna, are ram respirators and hence are constantly swimming. Thus, if they hear, they must be able to do so while swimming.

There are few data on hearing in any tuna species. Iversen (1967) measured behavioral hearing thresholds and found that yellowfin tuna (Thunnus albacares) could hear from 200 to 800 Hz and that swimming kawakawa (Euthynnus affinis) had a similar hearing range (Iversen, 1969). While there are no data on hearing in PBT, a study of the inner ear anatomy by Song et al. (2006) showed that the ear is quite similar to that of other tuna studied (Popper 1977).

METHODS AND PROCEDURES

Experiments were conducted in a 9.14 m diameter 1.65 m deep indoor cylindrical tank at the Tuna Research and Conservation Center (Stanford University) (Fig. 1). A “stimulus region” was located at one side of the tank and a feeding dispenser located near the ceiling above the tank. The feeding station consisted of a remote controlled food dispenser located near the perimeter of the tank and when trained fish approached the feeding site in response to a stimulus, food was released. The video cameras were also used to estimate both the speed of the fish and their location when the stimulus was presented. The depth of a fish was determined using pressure sensing tags.

Hearing thresholds for pairs of PBT were measured utilizing operant conditioning procedure with a food reward and a staircase psychophysical technique with 5 dB steps. Fish tended to swim around the perimeter of the tank. When they entered the “stimulus region,” a sound was played in the water (intervals between trials were randomly varied). Fish were trained to immediately swim to a feeding station to receive the food reward.

Pairs of fish were trained and used together rather than individually, because PBT are a schooling species and the animals were stressed when in the tank alone. The two fish typically swim close to one another and both responded to the sound stimulus at the same time, making it impossible to know if one or both fish were trained, or to determine thresholds for individual animals.

Training first involved getting the pairs of fish to learn that they were fed at the feeding station. Subsequently, feeding was paired with a light and sound stimulus and fish learned to make directed paths to the feeding station at an accelerated rate from wherever they were in the tank when the stimuli were presented. Over the course of a series of trials, the light was diminished and the fish would come to the feeding station in response to the sound. Fully trained fish did not take directed paths to the feeding station if they did not hear a sound, thus enabling threshold determination. Catch controls, where the experiment was conducted without a sound, demonstrated that the fish were responding only to the sound stimulus.

The acoustic stimulus was a windowed gated sinusoidal signal, which was presented only when both fish were passing through the “stimulus region”. The acoustic stimulus was produced by radially oriented piezoelectric line sources centered at the bottom of the tank which produced a circumferentially uniform sound field. The stimulus frequency band was limited to 325 to 800 Hz by the acoustics of the source and tank.
The acoustics of the tank was thoroughly characterized for both acoustic pressure and acoustic particle acceleration using hydrophones and two neutrally buoyant accelerometers with response axes oriented in the radial and vertical directions. The acoustic field measurements were performed with no fish in the tank both before and after the experiments.

**FIGURE 1.** Geometry of the experiment. The tank was 9.14 meters in diameter and 1.65 meters in depth. The source was located in the center of the tank, at the bottom and the food dispenser was located near the ceiling at the indicated location.

**RESULTS AND DISCUSSION**

Hearing thresholds for three pairs of PBT (all approximately 1 m in standard length) were measured at 325 Hz, 400Hz, 500 Hz, 600Hz, 700Hz, and 800 Hz. The swimming speed of the fish during the trials averaged a little over 2 m/sec. Three thresholds were obtained for each pair at each frequency. Fish, swimming at approximately 2 m/sec, quickly learned to approach the feeding station when they heard a sound. Typical results for two threshold determination tests are shown in Fig. 2. The tank characterization data was used to express the thresholds in terms of pressure and particle acceleration based on estimates of the location of each for each threshold test.

Mean pressure and particle acceleration thresholds, obtained by averaging over all runs and pairs, are shown in Fig. 3. The minimum mean threshold for acoustic pressure (84 dB re 1 µPa) occurs at 500 Hz whereas the minimum threshold for radial acceleration (-87 dB re 1 m/sec²) occurs at 400 Hz. It is possible that these thresholds are masked by noise.

The range of hearing reported here for PBT is somewhat narrower than for other fishes that do not have specializations for sound detection. An issue of interest is the sharp drop off in hearing sensitivity below 400 Hz for both pressure and particle motion. While this could be something to do with the nature of the tank, no measurements performed showed that there were acoustic issues. It is thus possible that PBT have much poorer low frequency hearing than other tunas (Iversen 1967, 1969) and other fishes that have no specializations.

An alternative suggestion, however, is that the limit on low frequency hearing shown in this study was because the fish was moving at a relatively high rate of speed (2 m/s) and the limiting factor may be flow noise. Indeed, the studies by Iversen did not have fish moving at this high speed, and to our knowledge there have been no studies of hearing in any species moving this rapidly during hearing tests. Thus, it would be of considerable interest to measure hearing in Bluefin moving at different speeds in order to test whether, at low speed they have better low frequency sensitivity.
FIGURE 2. Typical examples of threshold determination data. Vertical axis is the attenuation of the drive signal in dB. Stimulus was lowered by 5 dB if there was a response to a sound and raised 5 dB in there was no response. (a): Pair 2 at 700 Hz, the corresponding threshold derived from this run is -31.4 dB, (b): Pair 2 at 500 Hz, the corresponding threshold derived from this run is -47.5 dB.

FIGURE 3. Averaged acoustic thresholds for three pairs of Pacific bluefin tuna over the frequency range tested. (a) Thresholds expressed in terms of the applied acoustic pressure. (b) Thresholds expressed in terms of the applied radial acoustic particle acceleration.

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