

Aerial and underwater hearing thresholds for 100 Hz pure tones in two pinniped species

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Summary

Hearing sensitivities to 100 Hz pure tones of two California sea lions (*Zalophus californianus*) and one harbor seal (*Phoca vitulina*) were obtained. A combination of psychophysical techniques was used to determine absolute thresholds. Minimum audible pressure (MAP) measurements in air (using headphones) were 65 and 78 dB re 20 μ Pa for the harbor seal and one California sea lion, respectively. Underwater thresholds were 96, 120, and 116 dB re 1 μ Pa for the harbor seal and two sea lions, respectively. Minimum audible pressures were similar to published free-field thresholds of a harbor seal and a northern fur seal (*Callorhinus ursinus*). Comparisons between aerial and underwater thresholds indicate that the pinniped ear is more sensitive to water-borne than aerial low frequency sounds.

Key words: low frequency sound, minimum audible pressure, *Phoca*, psychophysics, *Zalophus*

Introduction

Marine mammals have been the subjects of audiometric testing for some 30 years (for reviews see Fobes and Smock, 1981; Schusterman, 1981), yet little is known about hearing sensitivities of any species below 1000 Hz. Much of this is due to interest in the biosonar capabilities of odontocetes, that use relatively high frequency signals. Further, mysticetes, which are known to produce low frequency signals, cannot be tested in a controlled laboratory setting. Recently, however, with increasing anthropogenic noise (e.g., oil drilling, shipping, jet planes, rocket launching, etc.), and its possible effects on both terrestrial and marine environments, there has been interest in the aerial and un-

derwater auditory sensitivity of marine mammals to low frequency sound. To this date, the only low frequency underwater hearing thresholds from marine mammals are those from a beluga, *Delphinapterus leucas* (Awbrey *et al.*, 1988; Johnson, 1989), a bottlenose dolphin, *Tursiops truncatus* (Turl, 1993), a Pacific white-sided dolphin, *Lagenorhynchus obliquidens* (Thomas *et al.*, 1993), and a manatee, *Trichechus manatus* (Gerstein *et al.*, 1993). Comparable low frequency aerial thresholds have been obtained from a California sea lion (Schusterman *et al.*, 1972) a northern fur seal (Babushina *et al.*, 1991) and a harbor seal (Terhune, 1991). Reluctance to test at low frequencies under water has to do with problems in signal production in relatively small test tanks. However,

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under the proper conditions, accurate thresholds at frequencies well below 500 Hz can be obtained through standard behavioral/psychophysical methods. In this study, we report minimum audible pressure (MAP) thresholds at 100 Hz in air for a California sea lion and a harbor seal. Underwater thresholds were obtained for both subjects in addition to a third California sea lion not tested in air.

Although ambient noise can be a problem in making aerial and underwater threshold measurements at low frequencies, there are many more difficulties inherent in measuring the responses of aquatic animals to such signals, especially when the wavelengths of the stimuli approximate the dimensions of the testing enclosure (Cummings *et al.*, 1975). From a physical standpoint, the reflective surfaces of artificial enclosures lead to characteristic sound pressure level maxima and minima within the tank. These levels vary with the position of the projector and receiver, as well as with frequency, and can span a full 80 dB from maximum to minimum sound pressure levels in tanks up to 7 m in diameter. Reflective surfaces also make directional hearing impossible, so researchers have often attempted to baffle their tanks with pieces of wood, mounds of sand, or rubberized horse hair, with varying degrees of success. Acoustic conditions in such artificial enclosures can make low frequency testing next to impossible to complete. Nevertheless, reliable low frequency thresholds can be obtained if two conditions are satisfied. First, the acoustic properties of the enclosure must be mapped prior to testing. Second, the subjects must be trained to maintain consistent positioning during all aspects of testing.

Initially, the acoustic response of a test pool to low frequency pure tones was mapped

prior to projected audiometric tests on three pinnipeds. Once a region of sufficient and constant signal intensity was located, the subjects were trained to station in that position for threshold testing. Such areas of maximal signal intensity arise due to a combination of direct and reflected signals, thus directional testing is impossible. However, when the positions of projector and receiver are maintained, the sound pressure level at a given location within the pool remains constant. This reverberent sound field can be taken advantage of for accurate low frequency threshold testing.

Materials and methods

Subjects

The subjects of aerial threshold testing were Rocky, a 17-year-old female California sea lion (*Zalophus californianus*), and Sprouts, a 5-year-old male harbor seal (*Phoca vitulina*). These two animals, as well as a 7-year-old female *Zalophus* (Rio) were the subjects of the underwater hearing experiments. All three animals were kept in free-flow salt water pools and adjacent haulout areas at Long Marine Laboratory in Santa Cruz, California. They were fed a mixed diet of herring and capelin (4-6 kg/day), and usually consumed one-third of a daily ration during acoustic test sessions.

Apparatus

Aerial: In-air threshold measurements were obtained outdoors, on haulout space adjacent to a 7.6 m diameter concrete pool. The response apparatus was an approximate cube measuring 45 x 42 x 45 cm. Two metal slots were attached to the inside front face of the apparatus. An opaque plexiglas door (39 x 45 cm) was mounted in these slots and connected to a rope and pulley assembly. A rectangular plastic paddle (19 x 14 cm) was bolted to a swinging PVC arm, and located

18 cm from the front face and midway between the top and bottom of the apparatus. A 25 cm length of PVC pipe was mounted to the left vertical support of the front frame. A stationing device (plastic ball) was attached to the end of this pipe (Fig. 1). The pipe/ball occupied the same horizontal plane as the response paddle (21 cm above the deck). Because of the height differences between the subjects, the apparatus was placed on cinder blocks for the sea lion, raising the height of the station arm to 61 cm.

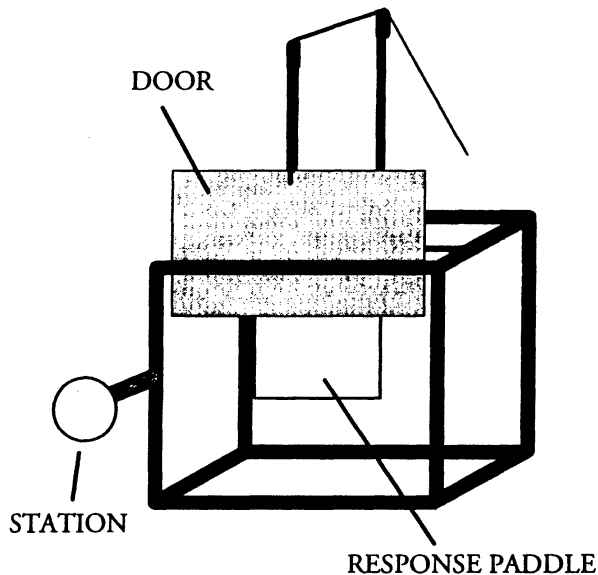


Figure 1. Diagram of the apparatus used for aerial tests.

Underwater: The response apparatus was similar to the one used in air, but larger. The dimensions were 43 x 135 x 100 cm. An opaque plastic door (62 x 39 cm) was held between two PVC slots mounted to the inside of the front face of the apparatus. The door was controlled by a rope and pulley assembly bolted to the top and rear of the apparatus. A rectangular plastic paddle (15 x 10 cm) was attached to a PVC arm, and located 18 cm back from the front face and 36 cm up from the bottom of the apparatus. The stationing device was a plastic ball placed at the end of a 35 cm pipe, mounted in the same

fashion as that used in air. When submerged, the ball was located 135 cm out from the wall of the pool and 157 cm below the rim of the pool.

Stimuli

Aerial: Pure tones were produced by a Stanford Research Systems DS345 function generator and SRS Arbitrary Waveform Composer software run on a 486-based PC. All waveforms had durations of 500 ms and rise/fall times of 40 ms. Frequencies of the downloaded signals were verified using a Hewlett Packard 5328A universal counter, and waveforms were monitored on a Hitachi V202 oscilloscope. Signals were triggered manually from the function generator. The output of the DS345 was fed to an H-P 350C stepwise attenuator, then to a JVC RX222 amplifier. Signals were presented to the subjects through Telephonics TDH-39 earphones secured in pockets of specially designed neoprene harnesses. The earphone openings were placed tightly over the ears of the subjects. Signal intensities were measured with a Bruel & Kjaer type 4153 artificial ear that coupled the earphone to a condenser microphone and a B & K type 2231 sound level meter. Noise levels were measured at the external meatus while the subject wore the earphones with an Etymotic ER-7C clinical probe microphone.

Underwater: Pure tones for underwater testing were generated in the same manner as the in-air signals. All waveforms had durations of 500 ms and rise/fall times of 40 ms. The signals were projected by a J9 underwater transducer supplied and calibrated by the Underwater Sound Reference Detachment of the U.S. Naval Research Laboratory. The J9 was suspended from a metal pipe that spanned the test pool, cradled on either side by wooden and PVC supports on each side of the pool rim. The J9 was placed 135 cm

away from the pool wall and 157 cm below the pool rim, on the horizontal axis shared by the response paddle and stationing arm. The distance between the J9 and the end of the stationing arm was approximately 490 cm. Sound pressure levels were recorded at the stationing device by an H56 hydrophone, also calibrated by the USRD of the Naval Research Laboratory. Signal waveforms were monitored by the V202 oscilloscope to confirm the presence of the signal on signal-present trials during all phases of testing the three animals (Fig. 2). Calibrations of signal and noise levels were made at the beginning and end of each session in a third-octave band centered at 100 Hz using a B & K 2130 frequency analyzer.

Procedure

Aerial: Before a trial, the subject was called out from the pool and the headphones were fitted by a trainer seated approximately 1.5 m to the side of the response apparatus. The subject was required to place its nose on the station before a trial began. When the subject was stationed properly, an assistant seated out of view behind the apparatus raised the door, exposing the response paddle. The opening of the door was served as a "ready" signal for the animal. The door remained open between 5 and 7 s. For a signal trial, the stimulus was triggered by the experimenter between 2 and 4 s after the door opened. A correct detection occurred if the animal pressed the paddle. If the trial was a catch trial (no signal), a correct rejection occurred if the animal remained stationed until the door was closed, signifying the end of the trial. Thus, opening the door began a trial, and a response or closure of the door terminated a trial. All correct responses were reinforced with a piece of fish. Incorrect responses were not reinforced. Neither time-outs nor punishment were used for incorrect responses.

Underwater: Underwater trials were conducted in essentially the same way as aerial trials, with some modification. Before the start of each underwater trial, the subject was instructed to swim down to the station by a trainer seated at the side of the pool. After the subject was properly stationed, a trial began when an assistant opened the door. Trial durations were similar to those used in air (5-7 s). The procedure was double blind (i.e., neither the trainer nor the assistant knew the trial, and the experimenter could not see the subject's response). A paddle press or lack of response was reported to the experimenter by the trainer. Reinforcement for correct responses was delivered by the trainer upon instruction by the experimenter. Incorrect responses were not reinforced.

Psychophysical techniques

Sessions and threshold determination were set up the same way for both aerial and underwater experiments. Signal and catch trials were presented quasi-randomly, with a conditional probability of 0.50 for either trial type (Moore and Schusterman, 1987). A combination of psychophysical methods were used to obtain thresholds. The first was a tracking or "staircase" method, in which the signal intensity was decreased by 4 dB for each correct detection (hit). Following the first failure to detect a signal (miss), the increments were changed to 2 dB (increased for misses, decreased for correct detections). The sound level was not altered after catch trials. After three to five sessions in which consistent reversals occurred, a threshold was estimated as the average between the upper and lower limits of the reversals. Generally, false alarms remained at or below 10% for each animal in all psychophysical testing sessions.

A final threshold was obtained using a mod-

Aerial and underwater hearing thresholds

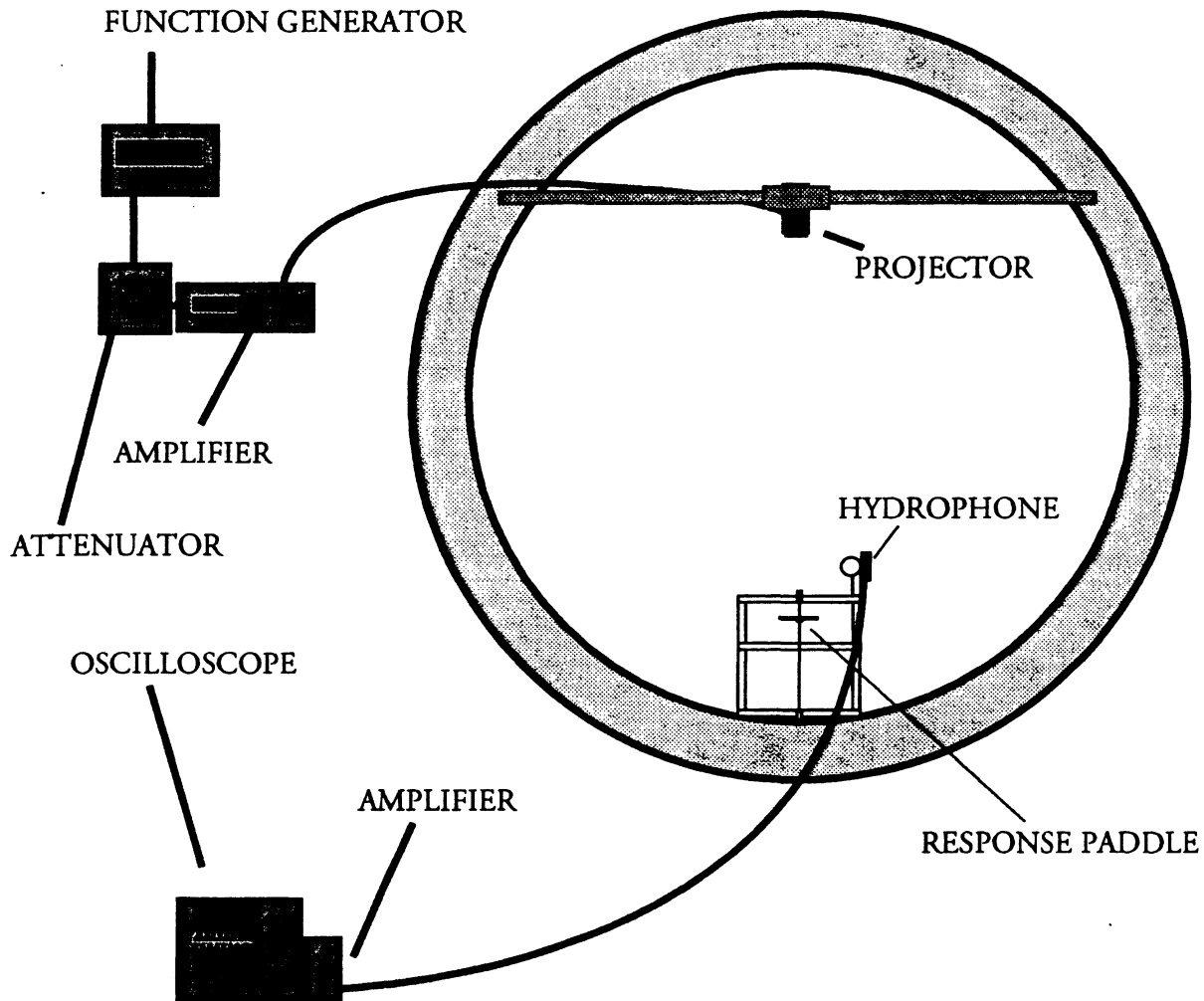


Figure 2. Schematic for underwater testing.

ified method of constant stimuli. A series of 6 sound levels (separated by 4 dB) were chosen from a 20 dB range surrounding the estimated threshold. Five trials of each signal level were arranged randomly in each 60 trial session, interspersed with 30 catch trials. After five days using this method, percent correct detections were plotted against signal level, and thresholds were calculated at the 50% level with false alarms remaining at 10% or less.

Results

Aerial psychometric functions for Rocky

(*Zalophus*) and Sprouts (*Phoca*) are shown in Figure 3. The range of sound pressure levels selected for the method of constants testing ranged from 0 or nearly 0% correct responses to 100% correct responses for both animals. Sprouts' threshold, determined by the 50% correct detection level, was approximately 65 dB re 20 μ Pa. This was roughly 13 dB lower than Rocky's threshold. Noise levels (measured with earphones on) at 100 Hz ranged from 35-40 dB re 20 μ Pa for both subjects. These levels were 15-20 dB lower than typical ambient noise conditions without earphones. Underwater thresholds for all three subjects are shown in Figure 4.



Figure 3. Psychometric functions for aerial hearing threshold testing at 100 Hz. a) Rocky (*Zalophus californianus*) and b) Sprouts (*Phoca vitulina*). Thresholds were determined by 50% correct detections.

Thresholds for both sea lions were similar (116 and 119 dB re 1µPa for Rio and Rocky, respectively). The harbor seal's underwater hearing sensitivity was 19 to 22 dB greater

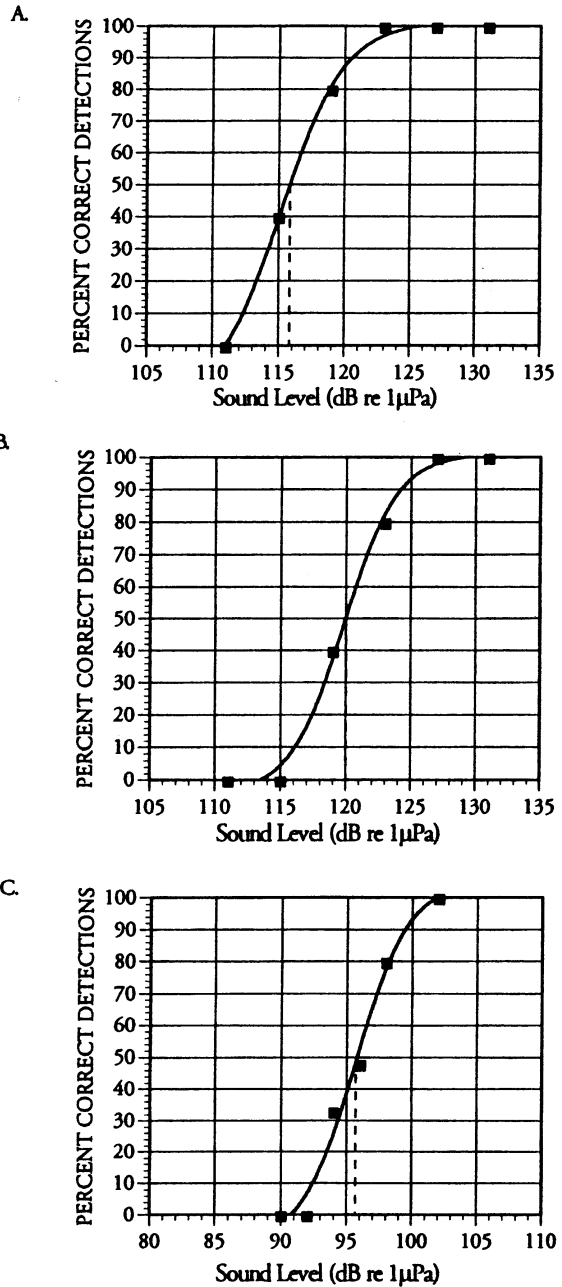


Figure 4. Psychometric functions for underwater hearing threshold testing at 100 Hz. a) Rio (*Zalophus californianus*), b) Rocky (*Zalophus californianus*), and c) Sprouts (*Phoca vitulina*). Thresholds were determined by 50% correct detections.

than that of the sea lions at this frequency. The ambient noise level at 100 Hz during testing was 71 dB re 1µPa.

Figure 5 compares aerial and underwater

Aerial and underwater hearing thresholds

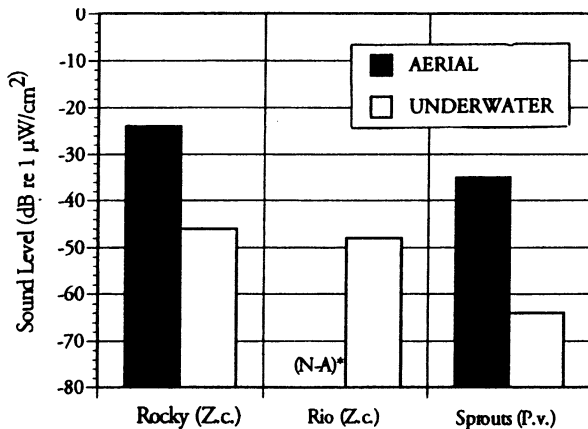


Figure 5. Comparison of aerial and underwater hearing intensity thresholds at 100 Hz for Rocky (*Zalophus californianus*), Rio (*Zalophus californianus*), and Sprouts (*Phoca vitulina*). Black boxes: aerial; open boxes: underwater.

thresholds for the subjects. Units have been converted from dB with reference to pressure to dB with reference to intensity in order to correct for the different acoustic impedances of the media (Moore and Schusterman, 1987; Wodinsky and Tavolga, 1964). Both subjects tested in air and underwater showed greater sensitivity under water, though this difference was more extreme (29 dB) for the harbor seal.

Discussion and conclusions

This is the first study to systematically compare aerial and underwater hearing sensitivity to very low frequency sounds in pinnipeds. In addition, aerial measurements were of minimum audible pressure rather than minimum audible field, since the tones were projected by earphones placed tightly around the head. The earphones served two purposes. First, they reduced the ambient noise at the meatus so that masking at this frequency was not a factor. Second, they reduced day-to-day variability in performance because the position of the sound source was constant throughout training and testing. In humans, low frequency hear-

ing thresholds obtained using headphones tend to be about 6 dB higher than those which rely on a sound field generated by external speakers (Syvian and White, 1933). This is presumed to result from masking by the amplification of physiological noise (the result of wearing headphones). However, because of high levels of low frequency ambient noise present at our facilities, it was impossible to test whether this "missing 6 dB" applies to pinnipeds as well. Sprouts' 100 Hz threshold was similar to those obtained from a harbor seal using a minimum audible field technique (70 dB re 20 μ Pa; Terhune, 1991). Rocky's threshold was 5 to 6 dB higher than that of a northern fur seal (72 dB re 20 μ Pa; Babushina *et al.*, 1992). Overall, the choice of psychophysical and signal presentation methods in this study negated much of the variability inherent in behavioral audiometric tasks; day-to-day threshold estimates rarely varied by more than 2 dB, and false alarm rates remained below 10%. Comparisons between aerial and underwater thresholds for Sprouts reflect a typical phocid pattern, in which underwater sensitivity is greater than that in air, regardless of frequency (Møhl, 1968; Terhune, 1991). Otariids, on the other hand, show much higher similarity between aerial and underwater sensitivities, these levels overlapping over much of the audible range (see Moore and Schusterman, 1987; Schusterman, 1981). Our results at 100 Hz suggest that this pattern may not hold true at very low frequencies. None of the subjects exhibited behavioral variability (e.g. dual thresholds during tracking sessions) that would indicate sensitivity to acoustic particle velocity as well as sound pressure (Turl, 1993). However, this cannot be ruled out, as measurements of particle velocity in relation to pressure have not yet been made in the test tank. These measurements, as well as further comparisons between aerial and underwater hearing

thresholds will be necessary, before any concrete conclusions are drawn.

The present results, as well as ongoing studies at frequencies between 200 and 1600 Hz, are important in light of the ecology of pinnipeds. Because of their amphibious existence, they are subject to disturbance from both aerial and underwater noise sources. Given that shipping, oil drilling, air traffic, rocket launching, and many other human-made noises are dominated by low frequencies, this and other studies are necessary to assess the possible effects of noise on the foraging, navigating, and social activities of pinnipeds and other marine mammals.

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