Chapter 41
Auditory Sensitivity and Masking Profiles for the Sea Otter (*Enhydra lutris*)

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Abstract Sea otters are threatened marine mammals that may be negatively impacted by human-generated coastal noise, yet information about sound reception in this species is surprisingly scarce. We investigated amphibious hearing in sea otters by obtaining the first measurements of absolute sensitivity and critical masking ratios. Auditory thresholds were measured in air and underwater from 0.125 to 40 kHz. Critical ratios derived from aerial masked thresholds from 0.25 to 22.6 kHz were also obtained. These data indicate that although sea otters can detect underwater sounds, their hearing appears to be primarily air adapted and not specialized for detecting signals in background noise.

Keywords Sea otter • Hearing • Audiogram • Noise • Masking

1 Introduction

Sea otters (*Enhydra lutris*) are amphibious coastal-living marine mammals that have faced numerous obstacles on their path to population recovery since being hunted to near extinction in the late nineteenth century. Despite international protection (Kenyon 1969) and "red" listing by the International Union for Conservation of Nature (2013) as an endangered species, some populations remain threatened and are considered vulnerable to a variety of environmental and anthropogenic pressures. Their dependence on restricted nearshore habitats also puts sea otters at risk for acoustic disturbance from activities occurring both on land and at sea. Growing concern about human-related impacts has led to intense and multidisciplinary efforts to improve the overall knowledge of this sensitive species. Although targeted research has been recognized as fundamental to their long-term recovery (US Fish and Wildlife Service 2003), the potential effects of anthropogenic noise on sea otters are not well understood, in part because their auditory biology has never been studied.

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In this psychoacoustic study, we investigated the auditory sense of sea otters by describing absolute hearing capabilities in quiet aerial and underwater environments. Sea otter hearing was also evaluated in a masking scenario to understand how baseline capabilities are altered by the simultaneous presence of noise. This study extends previous work conducted with sea otters in our laboratory, which provided estimates of the frequency limits of aerial hearing (Ghoul and Reichmuth 2012).

2 Assessment of Amphibious Hearing Capabilities

Aerial and underwater hearing profiles (audiograms) for the sea otter were obtained for a 14-year-old adult male southern sea otter (*Enhydra lutris nereis*) living in captivity (USGS 2788-97R). The otter was trained to perform an auditory go/no-go detection task that involved positioning at a listening station and responding to the presence of a tone with a nose touch to a response target (correct detection) and remaining motionless in the absence of a signal (correct rejection). A favored food reward was delivered to the sea otter after each correct response. During experimental sessions, the amplitude of the acoustic stimulus was progressively altered using an adaptive, up-and-down method. Hearing thresholds at each sound frequency were determined at the 50% correct detection level averaged across multiple sessions with a stable performance. The subject's response bias (i.e., the likelihood of false positives occurring during signal-absent trials) was maintained above 0% and below 30% throughout testing. This allowed for direct comparison of auditory thresholds obtained at different frequencies as well as between media (air and underwater).

2.1 Aerial Audiogram

The testing environment used during the aerial hearing assessment was a hemianechoic acoustic chamber specially designed for marine mammal audiometry (Reichmuth et al. 2013). At the beginning of each session, the sea otter voluntarily entered the chamber and positioned himself in front of a listening station to initiate testing. The acoustic test stimuli were frequency-modulated (FM) tones of 500 ms with a rise/fall time of 20 ms. These signals had narrow frequency bandwidths of 10% (approximately 1/8 of an octave) and were centered on the following 12 frequencies: 0.125, 0.25, 0.5, 1, 2, 4, 8, 16, 22.6, 32, 38.1, and 40 kHz. The temporal, spectral, and amplitude characteristics of the test signals were measured before every session. Background noise in the acoustic chamber was measured after each session. A test session typically comprised 30–45 trials and lasted 12–15 min. A minimum of three sessions showing stable performance was required for final threshold estimation at each frequency, which was determined from the three-session average.

The aerial audiogram for the sea otter, showing hearing threshold as a function of frequency, is in Fig. 41.1, left. Aerial hearing was most sensitive at 8 kHz, where the lowest threshold of −1 dB re 20 μPa was measured. The range of best sensitivity (defined as the frequency range audible at 10 dB above the lowest threshold)

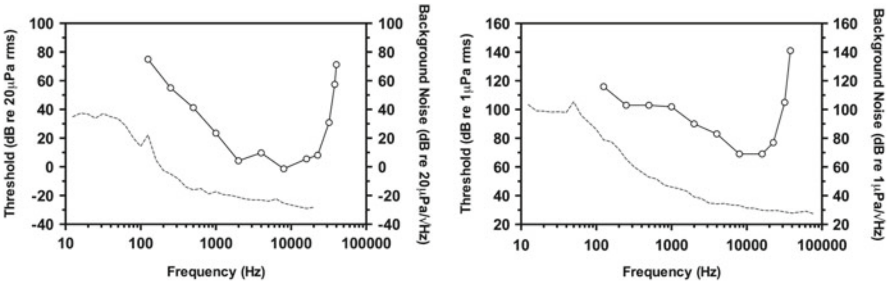

Fig. 41.1 Amphibious hearing profiles for a southern sea otter obtained using a psychoacoustic procedure. *Left*: Aerial audiogram showing absolute auditory detection thresholds plotted as a function of sound frequency. *Right*: Underwater audiogram with corresponding background noise, measured in the seawater testing pool. *Dashed lines*, acoustic background noise in the hemianechoic testing room. *rms* root-mean-square

extended from ~1.6 to 22 kHz. The subject's functional hearing range (defined as the range of audible frequencies at 60 dB) extended from 0.25 to 38 kHz. The audiogram determined for this sea otter had a typical U-shape, with a gradual roll-off in sensitivity on the low-frequency end (~18 dB/octave), and a sharp roll-off on the high end (~23 dB within a half-octave). Noise spectral density levels in the testing chamber (Fig. 41.1, left) decreased with increasing frequency, with levels dropping below 0 dB re 20 µPa/$\sqrt{}$Hz at frequencies above 0.25 kHz. The testing environment was sufficiently quiet to preclude influence by ambient noise.

2.2 Underwater Hearing Sensitivity

The methods used to test the sea otter subject's underwater hearing (i.e., sound generation and measurement, ambient-noise monitoring, psychophysical procedure, and final threshold determination) were similar to those used during aerial testing, with a few exceptions. The underwater hearing assessment was conducted in an acoustically mapped pool filled with seawater. The sea otter was trained to dive to an underwater listening station located 0.5 m below the surface where he performed the same go/no-go signal detection procedure as described in Section 2. To control for buoyancy effects, the otter was trained to maintain a vertical posture at the underwater listening station (i.e., oriented in a downward position) by using forepaw grips to stay submerged and hold his head in a fixed location. The acoustic stimuli and calibration procedures used during underwater testing were identical to those used for aerial testing. Testing occurred at 11 frequencies: 0.125, 0.25, 0.5, 1, 2, 4, 8, 16, 22.6, 32, and 38.1 kHz, with sounds projected from underwater transducers that were positioned to minimize spatial variability in the received sound field. Final absolute detection thresholds at each frequency were also determined in the same manner as for aerial testing, from an average of three thresholds obtained from individual test sessions.

The underwater audiogram for the sea otter subject is shown in Fig. 41.1, right. The subject's hearing was most sensitive at 8 and 16 kHz, where measured thresholds were the lowest at 69 dB re 1 μPa. The range of best sensitivity in water spanned ~4.5 octaves, from 4 to 22.6 kHz. The roll-off in high-frequency hearing was typically steep and had a 28-dB increase within a half-octave frequency step. Low-frequency hearing (0.125–1 kHz) was notably poor. The sea otter was unable to detect signals below 100 dB re 1 μPa within this frequency range. Noise spectral density levels in the underwater testing enclosure were sufficiently low to ensure that the measured thresholds were not influenced by background noise, especially at frequencies above 0.5 kHz, where noise levels were below 60 dB re 1 μPa/$\sqrt{\text{Hz}}$.

3 Aerial Critical Ratios

The auditory masking experiment was conducted in the same hemianechoic chamber as described in Section 2.1. Masked aerial thresholds were measured at eight frequencies: 0.25, 0.5, 1, 2, 4, 8, 16, and 22.6 kHz. The test signals were a subset of the same narrowband FM sweeps used to measure the aerial audiogram. The maskers consisted of spectrally flattened, octave-band noise centered at each of the eight frequencies that was projected continuously during the session from the same speaker used to project the test signals. Depending on the frequency, the spectral density level of the noise was either 10 or 20 dB above the subject's absolute threshold. The procedure used to measure masked hearing thresholds was similar to that used during absolute audiometry, except that the sea otter was trained to perform the signal detection task in the presence of continuous noise.

Critical ratios, calculated as the difference (in dB) between the SPL of the masked threshold and the spectral density level of the surrounding masking noise, were obtained for the sea otter at frequencies from 0.25 to 22.6 kHz. The critical ratios for this sea otter are shown as a function of sound frequency in Fig. 41.2.

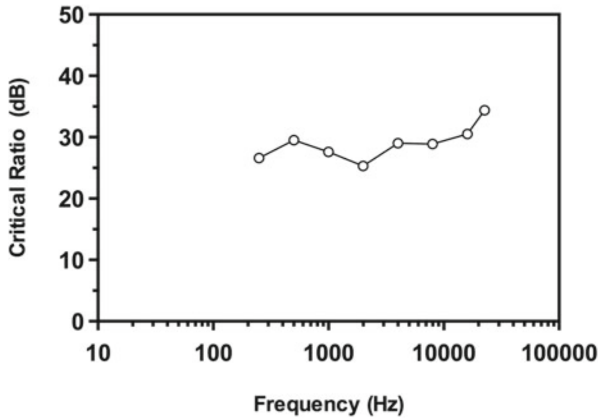

Fig. 41.2 Aerial auditory critical ratios for a southern sea otter are shown as a function of sound frequency

The masking data follow the same general trend as seen in other mammals tested, with critical ratios increasing gradually with increasing frequency. The lowest critical ratio estimated for this sea otter was 25 dB at 2 kHz, and the highest was 34 dB at 22.6 kHz. Below 2 kHz, the critical ratios were more variable with respect to frequency and higher than expected based on comparative data.

4 Conclusions

The amphibious auditory sensitivity profiles and critical ratios presented here for a trained sea otter represent the first hearing measurements for this species. Although these data were obtained from a single subject ($n=1$), the results are consistent with the available audiometric data for terrestrial carnivores as well as with the preliminary estimates of the hearing range in sea otters (Ghoul and Reichmuth 2012). Specifically, our results indicate that although sea otters are adapted for an aquatic lifestyle and spend most of their lives at sea, they have retained acute aerial hearing sensitivity that is comparable to that of terrestrial carnivores such as the domestic ferret (Kelly et al. 1986) and least weasel (Heffner and Heffner 1985). Underwater, hearing is less sensitive than in other amphibious marine carnivores such as seals and sea lions (see Reichmuth et al. 2013). Perhaps most notable is the finding that low-frequency hearing is worse than expected in both air and water. The validity of these hearing measurements for one sea otter subject is supported by the ambient-noise data, which confirm that the hearing measurements obtained were not limited by background noise in the testing environments. Compared with other marine carnivores tested under similar masking conditions (e.g., see Southall et al. 2003), sea otters do not appear to be specialized for hearing under conditions of noise despite living in somewhat similar coastal habitats. Information gleaned from corresponding anatomical studies, which are ongoing in our laboratory, will be required to determine the manner and extent to which the sea otter auditory system is adapted for an amphibious lifestyle.

The results of this study will inform current conservation and management issues and can be applied to environmental assessment problems in a manner similar to that conducted with pinnipeds and other marine mammals (e.g., National Research Council 1994, 2000, 2003, 2005; Richardson et al. 1995; Southall et al. 2007). However, the relatively poor low-frequency hearing documented in this study is significant and worthy of further investigation because most anthropogenic noise in marine environments, including that related to transportation and oil and gas production, is generated at frequencies below 1 kHz.

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