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Effect of Two Levels of Masking Noise on the Hearing Threshold of a Harbor Porpoise (*Phocoena phocoena*) for a 4.0 kHz Signal

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Abstract

The 50% detection hearing thresholds of a harbor porpoise for a 4.0 kHz narrow-band FM signal, presented at the background noise level in a pool and with two masking noise levels, were measured using a go/no-go response paradigm and an up-down staircase psychometric method. The masker consisted of a 1/6-octave noise band with a center frequency of 4.25 kHz. Its amplitude declined at 24 dB/octave on both sides of the spectral plateau. The absolute hearing threshold of the porpoise, found previously, was confirmed. The animal's auditory system responded in a linear fashion to the increase in masking noise. Since the narrow-band noise was off-center of the test frequency, the critical ratio of a harbor porpoise for 4.0 kHz tonal signals in white noise can at present only be estimated to be between 18 and 21 dB re: 1 μPa.

Key Words: anthropogenic noise, critical ratio, hearing, masking, harbor porpoise, odontocetes, *Phocoena phocoena*

Introduction

The harbor porpoise (*Phocoena phocoena*) is one of the smallest cetaceans and has a relatively wide geographical distribution (Gaskin, 1992). Like in other odontocetes, hearing in porpoises is very important for obtaining information about its environment by means of passive and active sonar (Kastelein et al., 1999). The underwater hearing of the harbor porpoise has been studied electro-physiologically (Popov et al., 1986; Bibikov, 1992) and behaviorally (Andersen, 1970; Kastelein et al., 2002, 2005) in relatively quiet conditions. Noise can compromise hearing by masking a signal. Masking occurs when one sound (the noise) interferes with the detection of another sound (the signal). The degree of interference depends upon the amplitudes of the two sounds and on the difference between the signal frequency and the noise frequency. Masking is greatest when the frequency of the noise is similar to the frequency of the signal (Wegel & Lane, 1924; Egan & Hake, 1950). Generally, hearing thresholds increase (hearing becomes less sensitive) when the background noise level increases as has been shown with behavioral methods for bottlenose dolphins (*Tursiops truncatus*) by Johnson (1968), Au & Moore (1990), and Finneran et al. (2002); for a beluga (*Delphinapterus leucas*) by Johnson et al. (1989); for a false killer whale (*Pseudorca crassidens*) by Thomas et al. (1990); and with the auditory evoked potential method for a harbor porpoise by Lucke et al. (2007), using offshore wind turbine noise as a masker.

It is unknown how well harbor porpoises can detect underwater signals in the presence of masking noises at various levels. In other mammals, thresholds for tonal signals increase linearly with increasing levels of the masking noise at or near the frequency of the tonal signals (Fay, 1988). When a trained harbor porpoise, which had just participated in a psycho-acoustic hearing study (Kastelein et al., 2002), became available for 4 months, the opportunity arose to study its hearing ability for 4.0 kHz signals with masking noise at two levels (53 and 60 dB re: 1 μPa/√Hz).

Materials and Methods

The study animal was a healthy 3-y-old male harbor porpoise (code PpSH047) with a body weight of 29 kg, a body length of 132 cm, and a girth in front of the pectoral fins of 66 cm (see Kastelein et al., 2002, for more details). He had recently participated in a basic underwater audiogram study (Kastelein et al., 2002) and was only available for 4 months for this study before being moved to another facility.

The porpoise was kept in an indoor concrete oval pool (8.6 m length × 6.3 m width, 1.2 m deep; Figure 1). The water temperature was on average 19.5° C and the salinity varied between 20 and 25% NaCl. The porpoise was trained to listen for signals while in a precise position in the pool (at the listening station). To maintain a constant sound level at the listening station, sound reflections from the water surface and the pool floor were reduced with two baffle boards. These were placed perpendicular to the animal's axis—one breaking the water surface and one at the pool floor (see Kastelein et al., 2002, for more details of the pool). The water pumps in a nearby engine room were switched off 10 min before each session and remained off during the sessions. All sources of noise from human activity in this indoor area were minimized during sessions. The signal and noise generation system was housed in a separate observation room (Figure 1). During the experiments, the controlling electronics and the operator were out of the porpoise's sight.

The time available was enough to test the animal's hearing sensitivity thoroughly at only one FM test signal (4.0 kHz) at three noise levels (background noise level in the pool and two masking noise levels). The choice of the test frequency was determined by the masking noise spectrum that could be generated by the available noise generator (see below). The test signal was produced by a waveform generator (Hewlett Packard, Model 33120A) and consisted of a narrow-band frequency-modulated (FM) signal. The center frequency was 4.0 kHz. The frequency fluctuated 100 times per second (100 Hz) between 3.96 and 4.04 kHz (1% modulation). An FM signal was used rather than a pure tone to reduce fluctuations in sound pressure level (SPL) at the location of the animal's head at the listening station (Finneran & Schlundt, 2007). The test signal, shaped and attenuated by a custom-built audiometer, had a duration of 2,000 ms, including 150-ms rise and fall times (steady state portion: 1,700 ms). The SPL at the porpoise's head while at the listening station was varied in steps of 4 dB. Before each session, the voltage output level of the system at the input of the transducer (while the attenuator was at the same setting as during calibration) was checked with an oscilloscope (Dynatek, Model 8120). The test signal was projected by an underwater LF piezoelectric transducer (Ocean Engineering Enterprise, USA, Model DRS-8; 25-cm diameter)

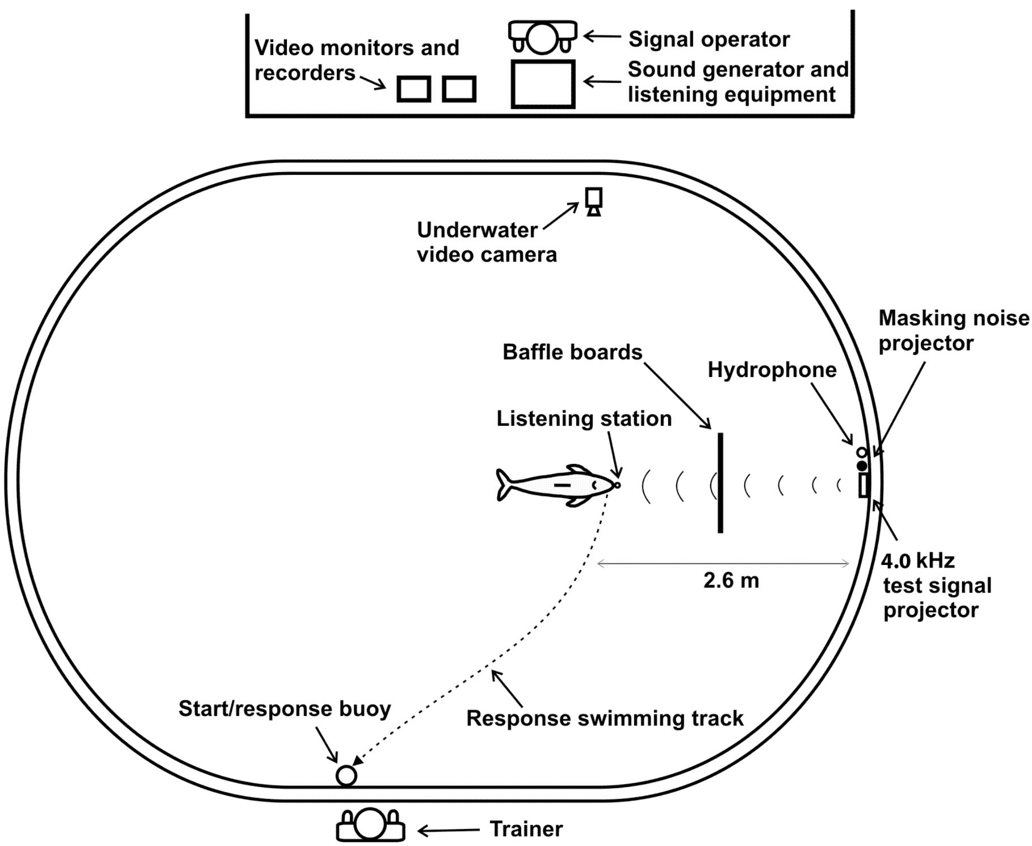

Figure 1. Top view of the study area, showing the study animal in position at the listening station and the locations of the signal operator and trainer; also shown is the porpoise's response swimming track. Two baffle boards were used: one just breaking the water surface and one at the pool floor.

with an impedance matching transformer. The transducer was directly in front of the porpoise, and its beam was aligned with the animal's body axis while he was at the listening station.

The masking noise at two levels was generated with a custom-built noise generator, which produced a fixed noise spectrum. The masker consisted of a 1/6-octave noise band with a center frequency of 4.25 kHz. Its amplitude declined at 24 dB/octave on both sides of the spectral plateau (4.1 to 4.4 kHz). At the test signal frequency (4.0 kHz), the masking noise spectrum level was 3 dB below the plateau level (Table 1). The intention was to produce a 1/6-octave noise band centered around 4.0 kHz. However, during the study, when funds became available to calibrate the system, the combination of the noise generator and transducer was found to produce a flat noise band between 4.1 and 4.4 kHz. The system was also calibrated at the end of the study, and the two measurements only differed by 2 dB. The noise was projected under water by a cylindrical transducer (LabForce 1BV, Model 90.02.01), which was omnidirectional in the horizontal plane and was fixed beside the transducer producing the 4.0 kHz test signal (i.e., at the same depth as the porpoise). Sound measurements were carried out as described by Kastelein et al. (2002). The 4.0 kHz test signal did not produce harmonics. The mean SPL from two calibrations was used to determine the hearing thresholds. The background noise level in the pool (up to 8.0 kHz) and the two masking noise levels were measured twice under the same conditions as during the study, using the equipment used to measure the test signals. The received noise levels are shown in Table 1 and Figure 2. Before each session, the test signal and the generated noise were checked by the signal operator via a hydrophone (LabForce 1BV, Model 90.02.01) placed next to the transmitting transducers and connected to an amplifier and loudspeaker.

Operant conditioning, using positive reinforcement, was used for all training. A trial began with the animal stationed at the start/response buoy (Figure 1). The amplitude in the first trial of each session was set at about 12 dB above the approximate detection threshold found in pretests for each of the three noise levels. When the trainer rang a bell, the animal swam to the listening station so that its external auditory meatus was 2.6 m from the sound source and 65 cm below the water surface (Figure 1). The animal's upper jaw was just above the station. While the porpoise was swimming to the station, either no additional noise was produced (the normal background noise level in the pool during sessions) or the masking noise was switched on at one of the two levels and was kept at this level until the animal had responded. The methodology was exactly as described by Kastelein et al. (2002). Sometimes the animal moved away from the listening station before a signal was produced. This was called a pre-stimulus response. To avoid the potential effects of learning by the animal or changes in the environment on the results, the order in which the three noise levels were tested was randomized among sessions.

A change in the animal's response from an apparently audible amplitude (a hit) to an apparently inaudible amplitude (a miss), and vice versa, is called a reversal. Sound levels at which reversals took place were taken as data points. The mean 50% detection threshold of the 4.0 kHz test signal in each of the three noise levels was defined as the mean amplitude over all the reversal pairs per noise level.

Data were collected between December 2000 and March 2001. One session was conducted daily (5d/wk) between 0830 and 0915 h at the time of the first feed of the day so that the porpoise had not been fed for 15 h before a session. In total, 720 trials (3 noise levels × 12 sessions/noise level × 20 trials/session) were used in the analysis.

Table 1. The three mean received noise levels (measured at 4.0 kHz and at the plateau level of the 4.1 to 4.4 kHz noise band), mean 50% detection thresholds of a male harbor porpoise for 4.0 kHz narrow-band FM signals at the three noise levels, total number of reversal pairs (collected in 12 sessions), and pre-stimulus response rate in all signal-present and signal-absent trials

	Noise		Audiology		
Type	Mean received noise spectrum level (dB re: 1 µPa/√Hz) at 4.0 kHz	Mean received noise spectrum level (dB re: 1 µPa/√Hz) of 4.1-4.4 kHz band	Mean 50% detection threshold ± SD (dB re: 1 µPa, rms)	Total number of reversal pairs	Pre-stimulus response rate (%)
Background	37	--	67 ± 2	72	7
Masking level 1	53	56	74 ± 3	75	5
Masking level 2	60	63	81 ± 3	80	6

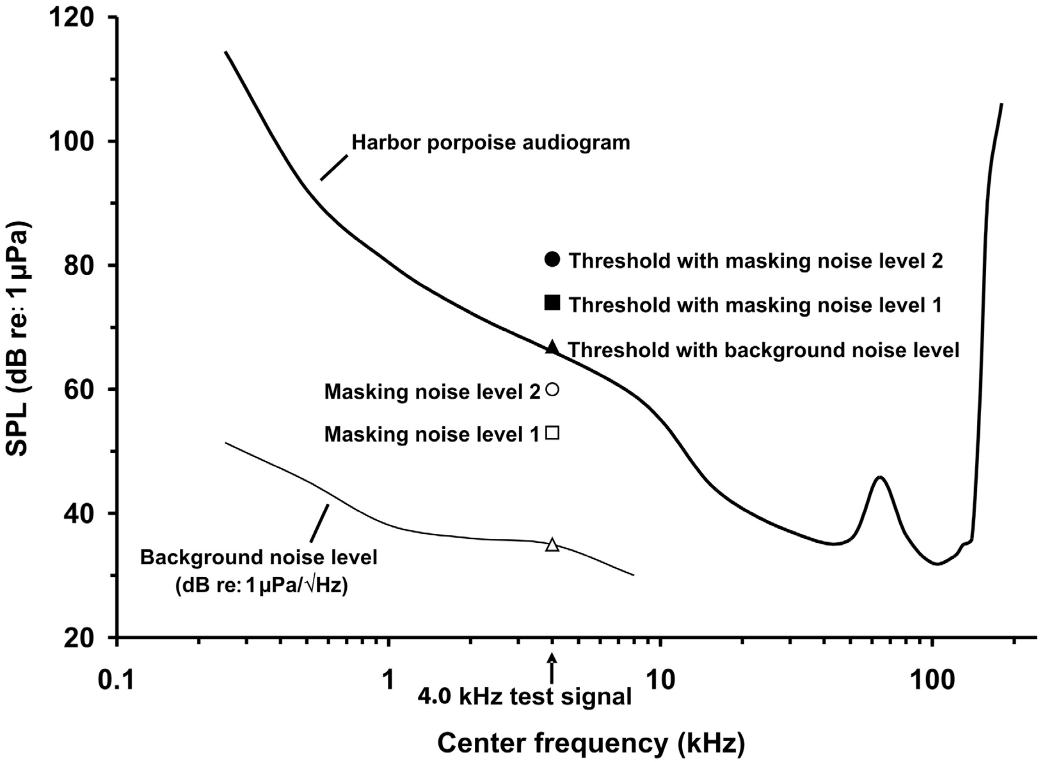

Figure 2. The mean 50% detection hearing thresholds of the harbor porpoise (dB re: 1 µPa, rms) for the 4.0 kHz narrow-band FM signal presented in the presence of background noise and of two masking noise levels (4.1 to 4.4 kHz); also shown is the audiogram of the study animal under similar background noise conditions and obtained with the same methodology (Kastelein et al., 2002). The spectral level (dB re: 1 µPa/√Hz) of the background noise in the pool is shown up to 8.0 kHz.

Results

The 50% detection hearing thresholds for the 4.0 kHz FM signals in the presence of three noise levels (background noise and two masking noise levels) are shown in Table 1 and Figure 2. In the background noise in the pool (received spectrum level 37 dB re: 1 µPa/√Hz), the mean 50% detection threshold level was 67 dB (re: 1 µPa, rms). At masking noise level 1 (received spectrum level 53 dB re: 1 µPa/√Hz), the mean 50% detection threshold was 74 dB (re: 1 µPa, rms). When the noise was increased by 7 dB to masking level 2 (received spectrum level 60 dB re: 1 µPa/√Hz), the mean 50% detection threshold also increased by 7 dB to 81 dB (re: 1 µPa, rms).

The critical ratio (CR) (in dB) is defined as the SPL of the 50% detection hearing threshold (in dB re: 1 µPa, rms) of a particular frequency in noise minus the power spectrum level of the noise at that frequency (in dB re: 1 µPa/√Hz; Fletcher, 1940). Since the auditory filter bandwidth of the harbor porpoise at 4.0 kHz is still unknown, it is not possible to calculate the CR exactly. However, based on the findings of this study, the CR for a 4.0 kHz signal is estimated to be between 21 dB (calculated from the noise spectrum level at 4.0 kHz) and 18 dB (calculated from the mean noise spectrum level from 4.1 to 4.4 kHz).

Discussion

The mean 50% detection threshold of the harbor porpoise for the 4.0 kHz test signal in the background noise of the pool was the same as the one measured during the year prior to the present study on the same animal in the same environment, using the same methodology (Kastelein et al. 2002; Figure 2). The 50% detection threshold found in background noise was 30 dB above the background noise spectrum level at 4.0 kHz, so the threshold was determined by the subject's sensitivity and was not masked by the background noise in the pool. The narrow-band noise at levels 1 and 2 (which were below the unmasked detection threshold) clearly masked the 4.0 kHz signal, and the CRs in the two noise levels were the same. CRs obtained using noise bands have been shown to be independent of masker level for most of the dynamic hearing range in other mammals (Fay, 1988).

CRs have been determined psycho-acoustically using white noise as a masker in bottlenose dolphins (Johnson, 1968; Au & Moore, 1990; Finneran et al., 2002), a false killer whale (Thomas et al., 1990), and a beluga (Johnson et al., 1989). In the beluga, detection of 4.0 kHz signals in white noise was tested at 4.0 kHz, and the CR was 22 dB, close to the CR range found in the present study for a harbor porpoise. When, in a future study, the auditory filter bandwidth of harbor porpoises becomes known for lower frequencies than the ones tested by Popov et al. (2006), the CR calculation in the present study can be reevaluated. A study similar to the present one, but with a wider frequency range, should be conducted with harbor porpoises. Tests should also be conducted with signals of ecological importance for harbor porpoises and with anthropogenic masking noises.

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