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Hearing Thresholds of Two Harbor Seals (*Phoca vitulina*) for Helicopter Dipping Sonar Signals (1.3-1.4 kHz)

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Abstract

Helicopter Long Range Active Sonar (HELRAS), used by lowering a transducer and receiver array into water from helicopters, produces ~1.3 to 1.4 kHz signals within the hearing range of many marine animals, including seals. The distance at which the HELRAS signals can be heard by seals is unknown but partly depends on the hearing thresholds of seals for the signals. The hearing thresholds of two adult harbor seals (*Phoca vitulina*) for HELRAS signals were quantified by means of a psychoacoustic technique. Hearing thresholds were obtained for five 1.25-s simulated HELRAS signals varying in harmonic content and amplitude envelopes. Hearing thresholds (50% detection rates) were similar: mean 51 dB re 1 μPa, root-mean-square (rms; broadband sound pressure level, averaged over the signal duration). Harmonic distortion in three of the five signals had no influence on audibility, as the harmonics were ≥ 20 dB below the hearing thresholds for the fundamental frequencies of the signals. The results of this study, combined with information on the source level of the signals, the propagation conditions, and ambient noise levels, allow the calculation of distances at which harbor seals can detect HELRAS signals. Under similar conditions, harbor seals are able to detect HELRAS signals at greater distances than harbor porpoises (*Phocoena phocoena*).

Key Words: acoustics, anthropogenic noise, detection, dipping sonar, hearing, helicopter, navy, phocids

Introduction

Navies worldwide contribute to the underwater background noise by employing active sonar systems. One type of low-frequency sonar is Helicopter Long Range Active Sonar (HELRAS) DS-100, a "dipping" sonar system used for the long-range detection of submarines (L3 Communications, Ocean Systems Division, CA, USA). HELRAS consists of a folding array of transducers and receivers that is lowered from helicopters to depths of up to 500 m and is the primary sonar system for the NH-90 helicopters used by several navies (including the German, Italian, and Netherlands navies). Once deployed and extended, the array is 2.6 m in diameter and produces sonar signals with source levels of 218 dB re 1 μPa^2m^2, rms (L-3 Ocean Systems, 2019).

Like other anthropogenic underwater noises, HELRAS signals may affect marine mammals. For management and policy, it is important to know if and how species react to these signals. In the North Sea, concerns about effects on harbor porpoises (*Phocoena phocoena*) have led to intensified regulation of sound with a focus on harbor porpoises. The hearing thresholds of harbor porpoises for HELRAS sonar signals have already been determined (Kastelein et al., 2011b). The harbor seal (*Phoca vitulina*) is a pinniped with a large geographical range in the coastal waters of the temperate zone of the northern hemisphere, overlapping to a great extent with the range of the harbor porpoise. Therefore, it is of interest to quantify the hearing sensitivity of harbor seals for the HELRAS signals for comparison with that of harbor porpoises.

To determine the distances at which harbor seals are able to detect HELRAS signals, the hearing threshold levels of seals for these signals need to be established. So far, the underwater hearing of harbor seals has been quantified by measuring their responses to pure tones (Møhl, 1968; Terhune, 1988; Turnbull & Terhune, 1990; Kastak & Schusterman, 1998; Southall et al., 2005; Kastelein et al., 2010; Reichmuth et al., 2013), narrow-band frequency-modulated (FM) signals (Kastelein et al., 2009b, 2018), one-third octave noise bands (Kastelein et al., 2009a), tonal signals of various duration (Kastelein et al., 2010), broadband impulsive sounds (Kastelein et al., 2013), and complex seal-scarer signals (Kastelein et al., 2015).

It is unclear whether narrow-band sweeps such as those in some HELRAS signals are just as detectable by harbor seals as pure tones. Therefore, the goal of this study was to determine the hearing thresholds of two harbor seals for various representative HELRAS signals. In combination with the source level, propagation conditions, and background noise, the hearing thresholds can be used to calculate the distance at which harbor seals can detect these signals under specific circumstances. For instance, this distance can be used in environmental impact assessments (EIAs). The hearing thresholds of the harbor seals for the HELRAS signals are compared to those of harbor porpoises for the same signals (Kastelein et al., 2011b).

Methods

Study Animals and Area

Two young female harbor seals with excellent hearing were used in this study (identified as harbor seals F01 and F02; 4 y old; body weight: ~45 kg). They had previously participated in three similar psychophysical hearing studies with tonal signals, one-third octave noise band, and signals of various durations (Kastelein et al., 2009a, 2009b, 2010). Variation in their performance in hearing trials was minimized by making weekly adjustments (usually in the order of 100 g) to their daily food ration, based on their weight and performance during the previous week, and the expected change in water and air temperatures in the following week.

The study was conducted at the SEAMARCO Research Institute, the Netherlands. Its location is remote and quiet. The outdoor pool (8 × 7 m; 2 m deep) was designed and built for acoustic research. For more details on the study area, see Kastelein et al. (2010).

Test Stimuli and Equipment Set-up

HELRAS produces continuous wave (CW) signals with durations of 0.313 to 10.0 s, at nominal frequencies of 1,311, 1,380, and 1,449 Hz, with various amplitude envelopes, or FM signals with durations of 0.156 to 5.0 s and bandwidths from 50 to 300 Hz. Three HELRAS signals considered as representative were provided by the manufacturer of HELRAS (L-3 Communications, Ocean Systems Division). The signals were manipulated to make them of consistent duration (1.25 s, which falls within the range used for HELRAS, and is suitable for shallow coastal waters). Two additional signals, similar to the original recordings but without harmonics, were synthesized to quantify the effect of harmonics on the harbor seals' ability to hear the signals. The signals with harmonic distortion exhibit a third and fifth harmonic, which are 20 to 30 dB below the level of the fundamental frequency. Thus, the seals' hearing sensitivity to five HELRAS signals was tested (Table 1). The HELRAS signals were created as WAV files with *Cool Edit Pro*. The spectra from recordings in the pool are shown in Figure 1, the waveforms in Figure 2, and the sonograms in Figure 3. The CWht (Continuous Wave, harmonics, tapered) signal was made from an original HELRAS signal recording of a 1,380 Hz CW with a cosine squared amplitude taper and harmonic distortion with a duration of 10 s by shortening the duration to 1.25 s while keeping the signal frequencies constant. The CWh (Continuous Wave, harmonics) signal was made from the middle section of a recording of a 1,380 Hz CW with an extended cosine amplitude taper and harmonic distortion with a duration of 5 s, with 50-ms cosine tapers at start and end. The DSh signal was made from a recording of a 1,430 to 1,330 Hz FM downsweep with a duration of 5 s by shortening the duration to 1.25 s while keeping the signal frequencies constant. The CW signal was a synthesized 1,380 Hz CW pulse with a duration of 1.25 s, with 50-ms cosine tapers

Table 1. The characteristics of the five 1.25-s HELRAS signals of which the hearing thresholds were determined for two harbor seals (*Phoca vitulina*)

HELRAS signal	Description	Relative level of 3rd harmonic	Relative level of 5th harmonic
CW	1,380 Hz continuous wave	No harmonic	No harmonic
CWh	1,380 Hz continuous wave with harmonic distortion	-25 dB	< -30 dB
CWht	1,380 Hz continuous wave with cosine squared tapers and harmonic distortion	-25 dB	< -30 dB
DS	1,430-1,330 Hz downsweep	No harmonic	No harmonic
DSh	1,430-1,330 Hz downsweep with harmonic distortion	-20 dB	< -30 dB

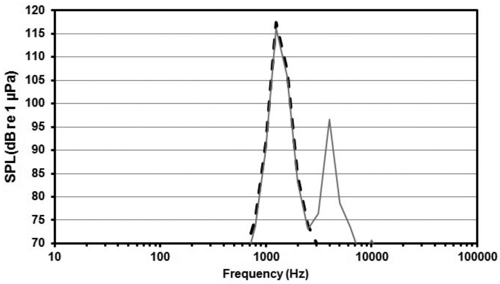

Figure 1. One-third octave (base 10) band sound pressure level (SPL) spectra (averaged over the signal duration) of the CW and DS signals (dashed line) and of the CWh, CWht, and DSh signals (solid line). Recordings from the pool.

at start and end. The DS signal was a synthesized 1,430 to 1,330 Hz FM sweep with a duration of 1.25 s, with 50-ms cosine tapers at start and end.

To prevent the production of unwanted on-offset transients, a 1 s silence was added before and after each signal in *Adobe Audition*, Version 3.0. The signals were generated on a laptop computer (Acer Aspire One, Model D250-0DK) from which the signal passed through a modified audiometer (Madsen Electronics, Midimate, Model 622, with extended frequency range and signal duration settings) which was used to control the amplitude of the signals. The free field sound pressure level (SPL) at the harbor seal's head while it was at the listening station could be varied in 2 dB increments. After the signals passed through an isolation transformer, they were projected underwater via a balanced tonpilz piezoelectric acoustic transducer (Lubell, Model LL 916).

Background Noise and Stimuli Level Measurements

Care was taken to make the harbor seals' listening environment as quiet as possible. Nobody was allowed to move within 15 m of the pool during sessions. Underwater background noise levels were measured three times during the 2-mo study period under the same weather conditions as during the test session conditions (no rain and wind force Beaufort 4 or below).

The one-third octave band SPL spectra of the background noise were determined, using the equipment described by Kastelein et al. (2010), in the 25 Hz to 80 kHz bands and were converted to the power spectral density ("pressure spectrum level," expressed in dB re 1 $\mu Pa^2/Hz$) by correction for the bandwidth (e.g., Kinsler et al., 2000). The mean (n = 3) background noise in the pool was very low (Figure 4); above 3 kHz, it was close to the self-noise of the recording equipment.

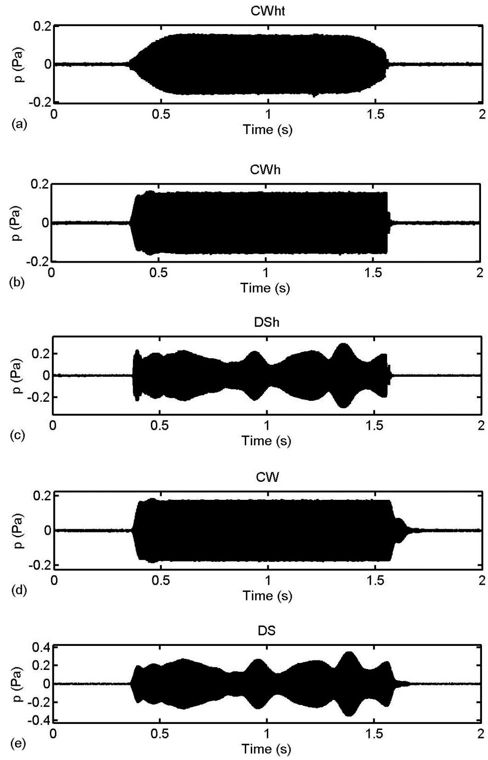

Figure 2. Waveforms of the five HELRAS signals, as recorded in the absence of the harbor seals (*Phoca vitulina*), at the location of a seal's head during hearing tests: (a) CWht, (b) CWh, (c) DSh, (d) CW, and (e) DS.

The received SPL (dB re 1 μPa, averaged over the t_{90} duration of the signal; Madsen, 2005) of each HELRAS signal was measured in the absence of the harbor seals, at the position of their head during the hearing tests.

Experimental Procedure and Analysis

For details of the methods, see Kastelein et al. (2010). The hearing sensitivity of the harbor seals for HELRAS signals was quantified by means of a psychophysical technique ("go/no-go" method). In signal-present trials, one seal at a time stationed (a maximum deviation of 3° from the beam axis was accepted), then waited for a random period (6 to 12 s) before the test signal was presented. In response to detecting a signal, the animal left the station. When the seal missed a signal, it remained at the listening station, and the trainer tapped on the side of the pool to call the animal back to the start buoy. In signal-absent (control or catch) trials, the seal stationed until the operator told the trainer after a random period (6 to 12 s) to end the trial by blowing softly on a whistle.

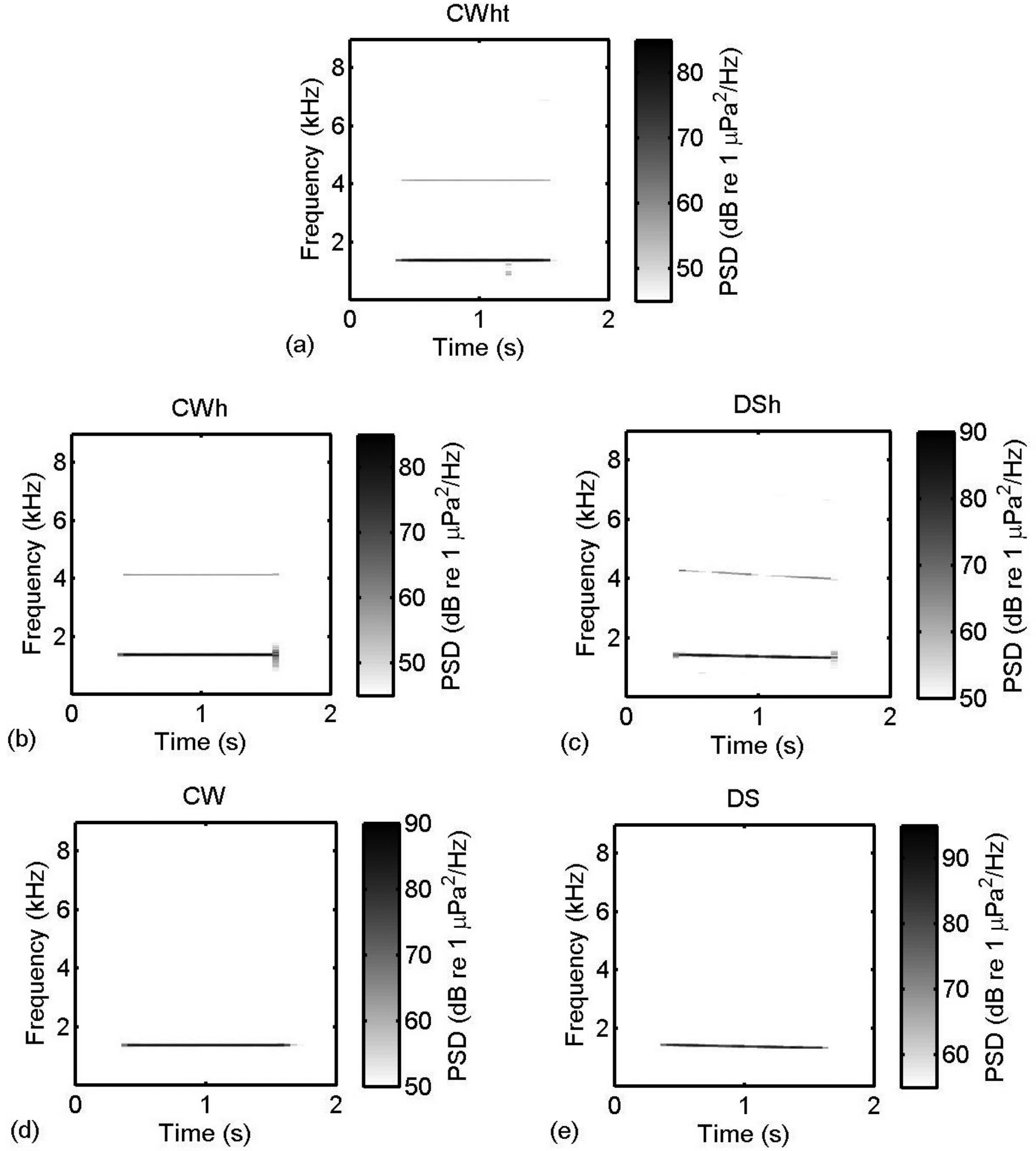

Figure 3. Sonograms of the five HELRAS signals, as recorded in the absence of the harbor seals, at the location of a seal's head during hearing tests: (a) CWht, (b) CWh, (c) DSh, (d) CW, and (e) DS. PSD = pressure spectral density.

In each session, one HELRAS signal was tested; its level was varied according to the 1-up 1-down adaptive staircase method. This conventional psychometric technique (Robinson & Watson, 1973) results in a 50% correct detection threshold (Levitt, 1971). If the animal detected a signal and responded to it (a hit), the level presented in the next trial was 2 dB lower than the previous level. If the animal did not detect a signal and remained at the station (a miss), the level presented in the next trial was 2 dB higher. A session usually consisted of 30 trials and lasted for approximately 15 min. Each session consisted of two-thirds signal-present trials and one-third signal-absent trials offered in random order.

Thresholds were determined for five HELRAS signals. Each signal was tested until at least 42 reversal pairs had been obtained per signal (collected in at least four sessions). For each session, a signal was randomly selected from the five HELRAS signals. One or two experimental

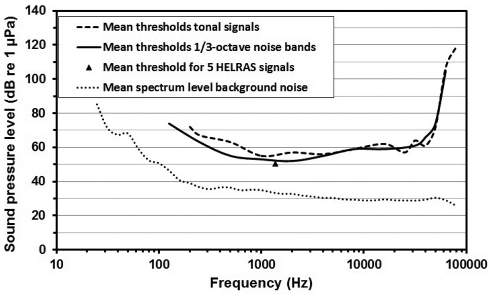

Figure 4. Mean 50% detection threshold SPLs (dB re 1 µPa) for the five 1,250-ms HELRAS signals of the two young adult female harbor seals (▲), their 50% detection hearing thresholds for 900-ms tonal signals (dashed line; Kastelein et al., 2009b), and the mean hearing thresholds of the same seals in a recent study (900-ms one-third octave noise bands; Kastelein et al., unpub. data). Also shown is the mean background noise spectrum level in the pool between 0.250 and 80 kHz (dotted line).

sessions per day were conducted (at 1330 and 1600 h) in September and October 2010.

The pre-stimulus response rate was calculated as a percentage based on the number of trials in which the animal left the station before a HELRAS signal (signal-present trials) or whistle (signal-absent trials) was produced, divided by the total number of trials conducted.

A switch from a test signal level that the harbor seal responded to (a hit) to an amplitude that it did not respond to (a miss), and vice versa, is called a reversal. The mean 50% detection threshold for a HELRAS signal was determined by calculating the mean amplitude of all reversal pairs for that signal (range: 42 to 58 reversal pairs).

Results

The mean pre-stimulus response rate (for both signal-present and signal-absent trials) varied between 2 and 8% in harbor seal F01, and between 5 and 11% in harbor seal F02, depending on the HELRAS signal (Table 2).

The 50% detection threshold SPLs for each harbor seal for each of the five HELRAS signals are shown in Table 2. All five HELRAS signals produced similar hearing thresholds (mean 51 ± SD 1.2 dB re 1 µPa; range: 47 to 53 dB re 1 µPa).

Discussion

Evaluation

The two harbor seals in the present study had the lowest hearing thresholds reported for harbor seals in the literature (Møhl, 1968; Kastelein et al., 2009a, 2009b, 2010; Reichmuth et al., 2013), and both had very similar hearing. Only minor differences in hearing thresholds were found in other research on harbor seals (mainly higher thresholds at the lowest frequencies, perhaps due to masked thresholds); this suggests that the thresholds found in the present study for the HELRAS signals are representative for young adult harbor seals. However, signal durations and spectra change over distance due to reverberations and absorption. Thus, the detection threshold for the HELRAS signals will also change over distance. The HELRAS signals tested were 1.25 s in duration, which was well above the integration time of harbor seals at this frequency (τ = 519 ms at 1 kHz; Kastelein et al., 2010). Due to propagation and reflection, signals tend to become longer as distance to the sound source increases, so audibility will not decrease due to a change in signal duration as distance increases.

Table 2. The mean 50% detection threshold SPL (± standard deviation [SD]) and pre-stimulus response levels (for both signal-present and signal-absent trials) of the two young adult harbor seals for the five HELRAS signals

	Harbor seal F01				Harbor seal F02			
HELRAS signal	Mean 50% detection threshold SPL (dB re 1 µPa) ± SD	No. of sessions	No. of reversal pairs	Pre-stimulus response rate (%)	Mean 50% detection threshold SPL (dB re 1 µPa) ± SD	No. of sessions	No. of reversal pairs	Pre-stimulus response rate (%)
CW	47 ± 2.0	5	50	7	50 ± 1.6	5	50	8
CWh	51 ± 1.6	4	44	6	51 ± 2.0	5	50	11
CWht	50 ± 1.7	5	58	6	50 ± 1.8	5	56	5
DS	52 ± 1.5	5	50	8	53 ± 1.9	4	44	8
DSh	49 ± 1.9	4	42	2	52 ± 1.6	4	42	5

The low variation in the thresholds found for the five HELRAS signals that were tested (see the SDs in Table 2) indicates not only that the levels of the HELRAS signals received by the harbor seals at the listening station were very stable, but also that the background noise level was either consistent between sessions or well below the hearing thresholds of the seals, or both (Figure 4).

Comparison of HELRAS Signal Thresholds with Tonal Thresholds

The 50% detection thresholds found for the 1.25 s HELRAS signals in the present study were only ~4 dB lower than the 50% detection thresholds found for 900-ms tonal signals in a previous study with the same animals (Kastelein et al., 2009b; Figure 4). This small difference could be explained by one or more of the following four factors: (1) improvement in the harbor seals' performance in psychophysical hearing tests over the years; (2) lowering of the threshold when a particular frequency is tested over a long period of time (the threshold for 1 kHz in a study after the present study indicates this; see Figure 4); (3) the 350-ms longer signal duration of the HELRAS signals; and (4) greater cognitive arousal caused by HELRAS signals, which are more complex than tonal signals.

The results of the present study indicate that the tonal audiogram can be used to roughly estimate the audibility of more complex narrow-band tonal signals in harbor seals. The harmonic distortion within three of the signals had little or no influence on the hearing threshold of the seals for HELRAS signals (as was seen in harbor porpoises when 1 to 2 kHz sweeps with and without harmonics were tested; Kastelein et al., 2011a). This can be explained by the tonal audiogram: the hearing threshold at the third harmonic frequency (4,140 Hz) is about 20 dB below the threshold at the fundamental frequency (1,380 Hz); at the fifth harmonic, the threshold is at least (depending on the signal) 30 dB lower (Table 1). The seals' hearing threshold for tonal signals over the 1 to 8 kHz range is fairly stable at 57 dB re 1 µPa (SD ± 1.7 dB; Kastelein et al., 2009b). Therefore, the relatively weak harmonics within the HELRAS signals used in the present study did not contribute significantly to their audibility for the harbor seals.

Comparison of Audibility of HELRAS Signals to Harbor Seals and Porpoises

The results from the present study can be compared directly with those from harbor porpoises because Kastelein et al. (2011b) used the same HELRAS sounds and methods used in the present study. At the HELRAS frequency (~1,400 Hz), the harbor seal's hearing threshold is approximately 25 dB lower than that of the harbor porpoise (under unmasked conditions for both species). A lower threshold was expected, as harbor porpoise hearing for tonal signals is less sensitive than harbor seal hearing below ~4 kHz (Kastelein et al., 2009b, 2017). Therefore, under the same background noise and propagation conditions, harbor seals are able to detect HELRAS signals at much greater distances than harbor porpoises. Audibility in itself may not be directly related to ecological effects, but their much lower hearing threshold suggests that harbor seals could react at a greater range to HELRAS signals than harbor porpoises. Therefore, research is required into other effects of the signals (e.g., disturbance, potentially resulting in changes in movements, feeding, breeding, and distribution) that may be of ecological relevance for harbor seals.

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