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Behavioral Responses of Harbor Porpoises (*Phocoena phocoena*) to U.S. Navy 53C Sonar Signals in Noise

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Abstract

Naval sonar systems produce signals that may affect the behavior of harbor porpoises (*Phocoena phocoena*), and behavioral responses may be influenced by the received signal and by the signal-to-noise ratio (SNR). The widely used AN/SQS-53C hull-mounted sonar system produces 1,600-ms signals with three components in the ~3.5 to 4.1 kHz band. To investigate the effect of the SNR on respiration rate (an indicator of the behavioral response to the sonar signals), two porpoises were exposed to 30-min playbacks of 53C sonar signals (96% duty cycle) in noise corresponding to sea state 6 conditions. Two signal-to-noise conditions were tested: 53C sonar was produced at an SPL of 117 dB re 1 μPa (SNR = 49 dB re 1 Hz), which caused no response; and at 122 dB re 1 μPa (SNR = 54 dB re 1 Hz), which caused an increased respiration rate in both porpoises. In quiet conditions, one of the porpoises had responded to the signal at approximately the same SPL (Kastelein et al., 2018). These measurements suggest that the behavioral responses of harbor porpoises to naval sonar signals are unaffected when the ambient noise is similar to that of wind noise up to sea state 6.

Key Words: anthropogenic sound, masking, navy, noise, odontocete, sea state, sonar

Introduction

The U.S. Navy uses hull-mounted sonar systems known as AN/SQS-53C (henceforth abbreviated as "53C"), which produce sounds in the ~3.5 to 4.1 kHz frequency range. Because of their high source level (SL), the sonar signals may affect a wide range of marine animals. The sonar system is used worldwide, and the areas ensonified during peace-time exercises overlap with the geographical range of some marine mammal species. Sound is particularly important for toothed whales (odontocetes), as they use it as a means of orientation and communication, and to locate prey, conspecifics, and predators (Richardson et al., 1995). Therefore, odontocetes can be disturbed by sounds, and noise in their environment may have physiological, auditory, and behavioral effects. The potential effects of naval sonar signals on the harbor porpoise (*Phocoena phocoena*) are of particular interest because this small odontocete has a very wide geographical range, including the coastal waters of the North Atlantic, the North Pacific, the North Sea, the Baltic Sea, and the Black Sea, and because the harbor porpoise has functional hearing over a very wide frequency range (Kastelein et al., 2017).

The effects of sonar signals in the 1 to 2 kHz, 6 to 7 kHz, and 25 kHz frequency bands on the behavior of harbor porpoises have been studied in low ambient noise levels (Kastelein et al., 2011, 2012, 2013, 2014, 2015a, 2015b). For the 53C sonar signal, a dose-response relationship has been established in low ambient noise levels (Kastelein et al., 2018). However, the audibility of a sound and its effect on behavior is expected to be determined not only by its sound pressure level (SPL) but also by the signal-to-noise ratio (SNR). Basic information on the effect of broadband masking noise on signal detection has been collected for only a few odontocetes (for review, see Erbe et al., 2016). Very little is known about the effect that masking by ambient noise may have on the behavior of odontocetes that are exposed to anthropogenic sounds. The effect of ambient noise on the behavioral response of harbor porpoises to sonar sounds (6 to 7 kHz sweeps) was measured by Kastelein et al. (2011); as the masking noise level increased, the response of the porpoises to the sonar signals decreased. The reduction in effect was probably due to the masking of the sonar signal by the noise.

Treating the 53C sonar signal as a narrowband signal with a sliding center frequency, the parameters of interest to masking are the critical ratio (CR) level and the extent to which the

SNR (defined as the difference between the signal SPL and the spectral density level of the masking noise) exceeds the CR. The effect of masking in harbor porpoises has so far been studied in three individuals; this research established the CR for frequencies covering the harbor porpoise's entire hearing range (Kastelein et al., 2008, 2009).

It is currently unknown how masking of the 53C sonar signals by ambient noise may affect the behavioral responses of harbor porpoises to those signals. The goal of this study is to investigate whether ambient noise similar to that associated with sea state 6 reduces the known effect of 53C sonar signals on the behavior of harbor porpoises.

Methods

Study Animals and Behavioral Response

The study was conducted with two harbor porpoises that had stranded and been rehabilitated. At the time of the study, the female, identified as harbor porpoise F05, was 6 years old, her body mass was around 42 kg, her body length was 152 cm, and her girth at the axilla was approximately 80 cm. The male, identified as harbor porpoise M06, was 3 years old, his body mass was around 33 kg, his body length was 127 cm, and his girth at the axilla was approximately 80 cm.

The hearing of the harbor porpoises in the frequency range of the sonar signals used in the present study (3.5 to 4.1 kHz) had been tested and was representative of animals of the same age and species; their 50% hearing thresholds were similar to those of three other young male porpoises (Kastelein et al., 2017). The animals had been exposed to the 53C sonar signal in a previous study (Kastelein et al., 2018).

The harbor porpoises were exposed to playbacks of 53C sonar signals during test periods, and the number of times they surfaced to breathe was compared during test and baseline periods to quantify their behavioral responses.

Study Area

The study was conducted at the SEAMARCO Research Institute, the Netherlands. Its location is remote and quiet, and was specifically selected for acoustic research. The animals were kept in a pool complex built for acoustic research, which consisted of an outdoor pool (12 m × 8 m; 2 m deep) connected via a channel (4 m × 3 m; 1.4 m deep) with an indoor pool (8 m × 7 m; 2 m deep). The study was conducted in the outdoor pool. The pool walls were made of plywood covered with polyester. To reduce the reflection of sound from the pool boundaries, the walls were covered with nets on which aquatic vegetation grew, and the bottom was covered with a 20-cm-thick layer of sloping sand. A research cabin housing the acoustic/video equipment and the operator was next to the pool. Details of the study area, including a figure showing the experimental set-up, are provided in Kastelein et al. (2018).

Acoustics

Acoustical terminology follows ISO (2017). Accordingly, throughout this article the term *sound pressure level* (SPL) refers to the level of the root-mean-square (rms) sound pressure, by definition.

Sound Source—The transducer (Lubell – LL1424HP) was placed at the southwestern end of the outdoor pool at 2 m depth. The linearity of the transmitter system used to play the 53C sonar signals was checked during each calibration and was found to deviate by at most 1 dB within a 42 dB range. The output of the sound system to the transducer was checked before each test session with a digital storage oscilloscope (Tektronix 2201) and a voltmeter (Agilent 34401A) by playing a 1-kHz pure tone WAV file.

Sound Measurements—The masking noise and 53C sonar signals were calibrated at the beginning, in the middle, and at the end of the study, under conditions similar to those during the test periods. The sound measurement equipment consisted of three hydrophones (Brüel & Kjaer [B&K] – 8106) with a multichannel high-frequency analyzer (B&K PULSE – Lan-xi type 3161-A-1/1) and a laptop computer with B&K PULSE software (*Labshop*, Version 20; sample frequency: 524,288 Hz). Before analysis, the recordings were high-pass filtered (cut-off frequency 100 Hz; 3rd order Butterworth filter; 18 dB/oct fall off) to remove low-frequency pressure fluctuations made by water surface movements. The system was calibrated with a pistonphone (B&K – 4229 with coupler WA 0658).

For the masking noise measurements, the one-third octave (base 10) band spectra of the SPL were determined via digital filtering of the time signal (IEC 61260-1:2014), averaging over a recording of 10 s duration. For each one-third octave (base 10) band of bandwidth B, the spectral density level in dB re 1 $\mu Pa^2/Hz$ of the masking noise was calculated by subtracting $10\log_{10}(B/(1\ Hz))$ dB from the SPL in that band.

Playback of 53C Sonar Signals—As the test stimulus, a 53C sonar signal supplied by the U.S. Navy was played back in the pool. Each signal consisted of three components. The first was an upsweep from 3.5 to 3.6 kHz. This was immediately followed by a continuous wave (CW1) of 3.75 kHz, which was followed, after a 100-ms silence, by a continuous wave (CW2) of 4.1 kHz. Each of the three components lasted for 500 ms, including 10-ms s-shaped on and off ramps, so that the 90% energy signal duration (T90) of each component, including ramps, was about 440 ms (Kastelein et al., 2018). The total duration of the complete 53C sonar signal, including the 100-ms silence, was 1,600 ms.

In a pilot study of 13 days, the SPL of the 53C sonar sound was increased in 3 dB steps (from 83 to 122 dB re 1 µPa) until a clear behavioral response by the harbor porpoises was observed in the simulated sea state 6 noise conditions. In the main study, the 53C sonar signal was played back at two SPLs: the one which did elicit a response in the pilot study and one ~6 dB lower which did not elicit a response. The higher SPL produced harmonics that were either buried in the masking noise (up to 8.5 kHz) or so low that they were barely audible. Specifically, the peaks visible in the spectrum at 11.7 and 15.0 kHz had an equivalent SPL (integrated in a small frequency band of width 10 Hz around each peak, each containing the peak itself and a small amount of system noise) of 45.0 and 46.4 dB re 1 µPa, respectively. These weak harmonics are not considered further because they were just below or ~1 dB above the hearing thresholds of harbor porpoises at those frequencies (Kastelein et al., 2017; Figure 1). Other signals can also be produced by the 53C sonar system, but the one used here is representative (Funnell, 2009).

In normal navy operations, long-range sonar systems are used at various duty cycles depending on the circumstances, expected targets, and target distances. Generally, a duty cycle of ~2.7% is used (interpulse interval: 58.4 s). However, in the present study, a 96% duty cycle (interpulse interval: 60 ms) resembling continuous active sonar was used (i.e., 60-ms silences between successive 1,600-ms sonar signals; Hickman & Krolik, 2012). This high duty cycle was used because it was difficult to elicit behavioral responses in the harbor porpoises by exposure to 53C sonar sounds at a duty cycle of 2.7% at the levels that could be produced in the pool.

Sonar sequences (WAV file; sampling: 44.1 kHz, 16 bit mono) were played back repeatedly by a laptop computer (Acer Aspire 5750) with a program written in *LabVIEW* to an external data acquisition card (National Instruments – USB 6259), the output of which could be controlled in 1 dB steps with the *LabVIEW* program. The output of the card went through a ground loop isolator and a custom-built buffer to a custom-built buffer/mixer, then to a custom-built variable passive low-pass filter (set to 6 kHz), after which it went to a power amplifier (East &West Inc. – HS1800), which drove the Lubell transducer through an isolation transformer (Lubell – AC1424HP).

The signal SPL, in dB re 1 µPa, was calculated by averaging over the duration of five consecutive signals. For one signal, the SPLs of the three individual components of the signal were determined by averaging over each component T90. For this purpose, the start and end of the time intervals were selected from the input voltage signal of the transducer. One-third octave (base 10) band spectra of the SPL were determined via digital filtering of the time signal.

SPL Distribution in the Pool (53C Sonar Signal)—To determine the SPL received by the harbor porpoises, the SPL during playback of the sonar signals was measured at 27 locations in the pool (on a horizontal grid of 2 m × 2 m), simultaneously at three depths per location on the grid (0.5, 1.0, and 1.5 m below the water surface), using three hydrophones (B&K – 8106). At each measurement position, each component of the signal was measured separately. Thus, 81 (27 × 3) measurements were made. The level of the spatially averaged mean-square sound pressure (abbreviated

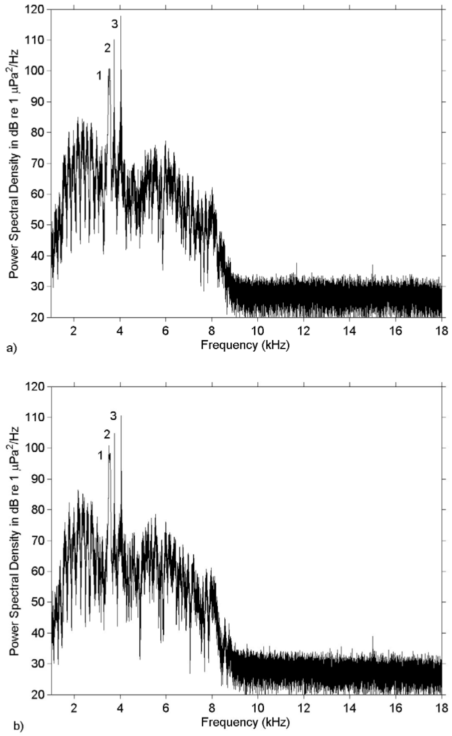

Figure 1. The power spectral density of the 53C sonar signal played back at the higher SPL used in the study (a) and at the lower SPL (b), recorded at 2 m from the sound source at a depth of 1 m. Upsweep (3.5 to 3.6 kHz FM), CW1 (3.75 kHz CW), and CW2 (4.1 kHz CW) are labeled as 1, 2, and 3, respectively. Three consecutive pulses are included in the measurement for an averaging time of 4.98 s.

as Lrec) in the pool was calculated based on the power sum of the 81 SPL measurements (Figure 2).

Masking Noise—The normal background noise level in the pool was low and was similar to the sound associated with sea state 0 (Figure 3). The 53C sonar signals were played back with masking noise resembling the sound associated with sea state 6 (Wenz, 1962) in the frequency range 2 to 6 kHz. This masking noise was produced by means of a laptop computer: a WAV file was created with a sound-generating program (*Adobe Audition*, Version 3). The frequency band includes the frequencies of the 53C sonar signals (3.5 to 4.1 kHz). The output of the laptop computer went to the buffer/mixer used to produce the sonar signals and, thus, reached the underwater transducer via the power amplifier and isolation transformer used for those sounds. The output from this part of the sound system to the transducer was monitored during each test session by means of the digital storage oscilloscope (Tektronix 2201) and the voltmeter (Agilent 34401A).

Signal to Sea State 6 Noise Ratio—The level of the 53C sonar signal was controlled independently of the simulated sea state 6 noise, which was kept fixed at the level shown in Figure 3. The signal gain was increased in steps of 6 dB until an obvious difference was seen between the number of times the harbor porpoises respired when the sonar signals were on and off. Two levels were selected to be tested (Lrec = 116.7 and 121.8 dB re 1 µPa; Figure 4). The SNR was calculated in dB re 1 Hz as the difference between the signal SPL and the spectral density level of the masking noise (Figure 5).

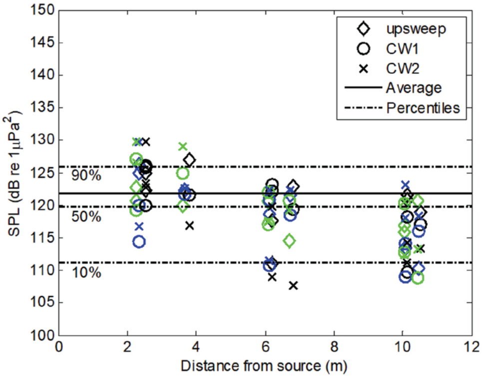

Figure 2. The SPL distribution of the 53C sonar signals at the 27 measurement positions vs distance (slant range) to the source (due to symmetry, some of these positions are at identical distances). At each measurement position, the three signal components (upsweep, CW1, and CW2) are shown, making a total of 81 measurements. The symbol colors represent the depth (black: 0.5 m, blue: 1.0 m, and green: 1.5 m). The Lrec in this case was 121.8 dB re 1 µPa (solid line), and the median SPL (50th percentile) was 119.8 dB re 1 µPa. The dashed lines show the 10th, 50th, and 90th percentiles. See Table 1.

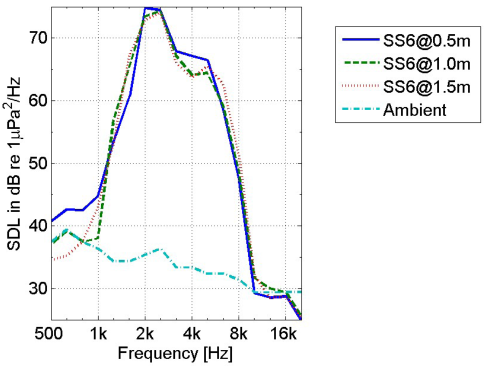

Figure 3. The mean one-third octave (base 10) band sea state 6 noise (SS6) spectral density level (SDL) at depths 0.5 m (solid line), 1.0 m (dashed line), and 1.5 m (dotted line), measured with a hydrophone at about 2 m from the source. Also shown (dash-dot line) is the normal background (ambient) noise level in the pool between 500 Hz and 20 kHz. At frequencies above 3.15 kHz, the ambient noise levels were below instrumentation self-noise levels.

Table 1. Summary of the spatially averaged mean-square sound pressure levels (Lrec) of the two 53C sonar signal levels and mean sound pressure level (SPL; 10th, 50th, and 90th percentiles) and mean signal-to-noise ratio (SNR; 10th, 50th, and 90th percentiles).

	SPL (dB re 1 µPa)			SNR (dB re 1 Hz)		
Lrec (dB re 1 µPa)	SPL10	SPL50	SPL90	SNR10	SNR50	SNR90
116.7	106.3	114.0	120.6	42.5	48.5	54.9
121.8	111.2	119.8	126.0	47.0	53.3	59.2

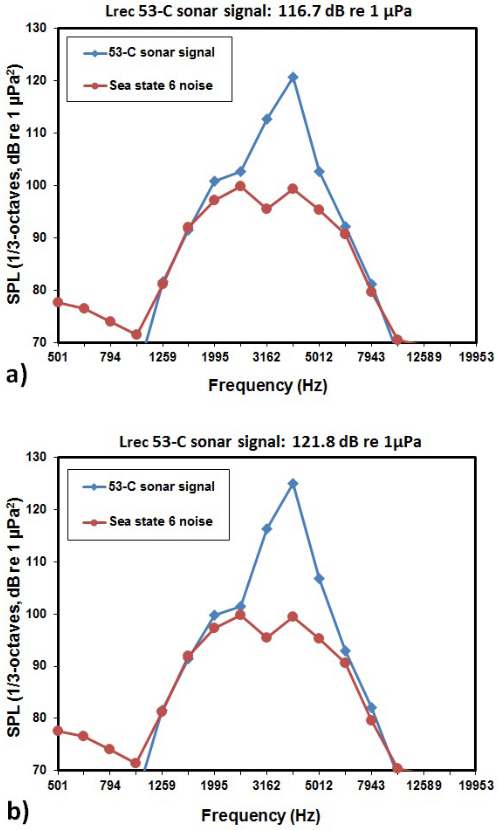

Figure 4. The one-third octave spectra of the 53C sonar signal and the sea state 6 noise measured 1 m from the sound source at a depth of 1 m, shown with the Lrec of the 53C sonar sound at 116.7 dB re 1 µPa, to which the harbor porpoises did not react (a), and at 121.8 dB re 1 µPa, to which the porpoises did react (b).

Video Monitoring

The animals' behavior was filmed from above by a waterproof action camera (GoPro 3) with a wide-angle lens (for details, see Kastelein et al., 2018). The audio part of the sea state 6 noise and the 53C sonar signals were added to the action camera's video recording via a custom-built hydrophone and a custom-built pre-amplifier of which the output went to a small speaker glued to the waterproof housing of the action camera. The output was also fed to an amplified speaker so that the operator in the research cabin could monitor the masking noise and the 53C sonar signals during test sessions.

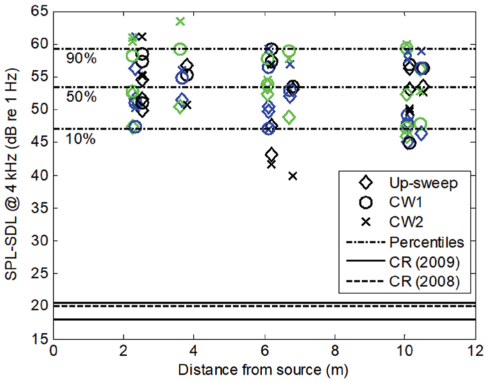

Figure 5. The SNR distribution of the 53C sonar signals (broken down into the three signal components: upsweep, CW1, and CW2) as a function of the distance to the transducer (81 measurements; nine for each depth and component). The symbol colors represent the depth (black: 0.5 m, blue: 1.0 m, and green: 1.5 m). Median SNR = 53.3 dB re 1 Hz (higher SPL, gain = 0 dB). The dashed lines show the 10th, 50th, and 90th percentiles. See Table 1 for other percentiles and SPL values. The variation in SNR in range is smaller than the variation in signal SPL (the dynamic range was chosen to facilitate comparison with Figure 2). The lines at the bottom of the graph show critical ratio (CR) measurements at 4 kHz for three other harbor porpoises—one from Kastelein & Wensveen (2008; dashed line) and two from Kastelein et al. (2009; solid lines).

Experimental Procedures and Analysis

To ensure that the harbor porpoises were always visible and could be distinguished from each other on the video recordings, they were marked with zinc ointment at the start of each day. The ointment was applied dorsally between the blowhole and the dorsal fin; a different pattern was used for each animal.

Each morning at around 0800 h, the transducer producing the playback signal and sea state 6 noise was positioned in the outdoor pool. At least 1 h later, when a session began, the masking noise was switched on. One 30-min baseline session (without 53C sonar signal) followed immediately by one 30-min exposure session (with 53C sonar signal, duty cycle 96%; fixed gain throughout the session) was conducted per day, beginning between 0900 and 1500 h.

Behavioral responses to the 53C sonar signals were quantified six or seven times at signal Lrec = 116.7 dB re 1 µPa (median SNR = 49.0 dB re 1 Hz) and five or six times, depending on the animal, at Lrec = 121.8 dB re 1 µPa (median SNR = 54.2 dB re 1 Hz). These two Lrec values were tested in random order.

Table 2. Results of paired *t* tests comparing the numbers of surfacings (respirations) during baseline and test periods, separately for each of the two harbor porpoises and each of the two signal levels, for which the corresponding Lrec = 117 and 122 dB re 1 µPa and SNR = 49 and 54 dB re 1 Hz. All baseline and test periods took place with noise similar to that associated with sea state 6. During test periods, the porpoises were exposed to playbacks of 53C sonar signals. In both cases, a significant *p* value (*) indicates that significantly more surfacings were observed during test periods than during baseline periods. Exact *p* values are shown. *t* = test statistic, *t* test.

			Mean no. of respirations (± SD)			
Lrec (dB re 1 µPa)	Harbor porpoise	Sample size	Baseline (No 53C sonar)	Test (With 53C sonar)	*t*	*p*
117	F05	6	85 ± 15	85 ± 17	-0.18	0.864
122	F05	5	86 ± 17	89 ± 16	-4.35	0.012*
117	M06	7	85 ± 9	84 ± 12	0.32	0.757
122	M06	6	78 ± 8	99 ± 9	-8.36	0.000*

Tests were not carried out during rainfall or when wind speeds were above Beaufort Force 4 (though high wind speeds did not create as much noise in the pool as would occur at sea because the pool was in a sheltered location and the rim of the pool extended above the water surface by 30 cm). The study was conducted in May and June 2017.

For each animal and signal gain (i.e., Lrec) separately, numbers of surfacings (respirations) counted during test and baseline periods were compared by means of a paired *t* test. For all analyses, the level of significance was 5% (Zar, 1999), and data conformed to the assumptions of the tests used (Ryan-Joiner test of normality on test-baseline values, $p > 0.100$ in all four tests; see Zar, 1999).

Results

When the Lrec was 117 dB re 1 µPa (SNR = 49 dB re 1 Hz), no behavioral response to the sounds was recorded (i.e., the harbor porpoises' mean respiration rates were similar in the baseline periods and in the exposure periods). However, when the Lrec was 122 dB re 1 µPa (SNR = 54 dB re 1 Hz), both harbor porpoises responded to the 53C sonar signals by significantly increasing the number of times they surfaced and respired (Table 2).

Discussion and Conclusions

Evaluation

The present study was conducted with two animals with hearing that was probably representative of that of other harbor porpoises of their age (Kastelein et al., 2017). However, little can be said about whether their responses were within the range of responses that would be shown by other individuals of this species. If possible, behavioral response studies should be conducted with as many animals as possible, as responses to acoustic stimuli vary between individual harbor porpoises (Kastelein et al., 2000, 2001, 2008). Behavioral responses to sounds are also context-dependent, depending on the occurrence of attractive and aversive components in the environment. The specific conditions of the pool do not occur in the wild, though situational contexts in the wild are innumerable. However, it is unlikely to be possible, in the near future, to conduct a similar experiment with other harbor porpoises, as the number of captive harbor porpoises is small, and most facilities are not designed for this type of behavioral response study.

The behavioral threshold SPL was similar for both harbor porpoises; however, it is possible that the animals influenced each other's behavior. The porpoise with the lower behavioral response threshold may have influenced the other porpoise to react at a lower threshold than it otherwise would have. In the wild, porpoises usually live solitarily and so are less likely to influence one another's behavior than was seen in the present study in a pool.

The difference in the harbor porpoises' mean respiration rate during baseline periods before exposures to 117 and 122 dB signals was simply due to daily variation in respiration rate, probably related to weather conditions or other contextual differences. Each test period was compared with the baseline period immediately preceding it so that the context was similar and variations were controlled for by the paired experimental design.

The simulated sea state noise used in the present study was based on random Gaussian white noise. In reality, ambient noise levels fluctuate temporally; the acoustic environment consists of noise in which the energy across frequency regions is coherently modulated in time. Branstetter & Finneran (2008) showed that bottlenose dolphins (*Tursiops truncatus*) have lower masked hearing thresholds in temporally fluctuating co-modulated noise than in constant-amplitude Gaussian white noise with the same spectrum level.

In normal navy operations, long-range sonar systems are used at various duty cycles depending on the circumstances, expected targets, and target distances. However, 2.7% (i.e., one 1,600-ms sonar signal every 60 s) is the most commonly used duty cycle at the moment. The duty cycle used in the present study is much higher (96%; i.e., 60-ms silences between the 1,600-ms sonar sounds) and resembles continuous active sonar (CAS). At lower duty cycles, the behavioral response thresholds are expected to be higher than those found in the present study. In fact, at a duty cycle of 2.7%, Kastelein et al. (2018) were not able to elicit behavioral responses in the harbor porpoises which participated in the present study, even at an Lrec of 143 dB re 1 µPa.

Signal-to-Noise Ratio

The measured SPLs (in the 4 kHz one-third octave [base 10] band) of the 3.5 to 4.1 kHz 53C sonar signal and of the ambient noise are compared in Table 1. The SNR is characterized by the difference between the signal SPL and the spectral density level of the ambient noise. As shown in Table 2, the 53C sonar signals elicited behavioral responses in the harbor porpoises only when the Lrec was 122 dB re 1 µPa (median SNR was 54 dB re 1 Hz, 34 dB above available CR measurements for the same species which is around 20 dB; Figure 5; Kastelein & Wensveen, 2008; Kastelein et al., 2009). In a previous study (Kastelein et al., 2018), conducted under quiet conditions (when both porpoises had a mean respiration rate of ~81 to 84 per 30 min in baseline period, similar to that of the present study), porpoise M06 responded by increasing his respiration rate at approximately the same Lrec (≥119 dB re 1 µPa) as found in the present study. Porpoise F05 also increased her respiration rate, but her response was not statistically significant (Kastelein et al., 2018). The noise level corresponding to sea state 6 in the 2 to 6 kHz band did not mask the 53C sonar signals in the present study at all. If the noise level had been high enough to cause a degree of masking, a behavioral response would have been expected to occur to 53C sonar signals at a higher Lrec value than found in the present study, as was also found in quiet conditions (Kastelein et al., 2018). We conclude that, for these 53C sonar signals and for harbor porpoises, the received SNR needs to be lower than 54 dB re 1 Hz for the noise to have a masking effect, which influences the behavioral response threshold SPL. When a 53C sonar signal would be completely masked (i.e., not detected at all; SNR < 20 dB), no response would be elicited.

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