Aquatic Mammals 2014, *40*(3), 232-242, DOI 10.1578/AM.40.3.2014.232

Effect of Series of 1 to 2 kHz and 6 to 7 kHz Up-Sweeps and Down-Sweeps on the Behavior of a Harbor Porpoise (*Phocoena phocoena*)

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Abstract

To compare the effect of naval sonar up-sweeps and down-sweeps on the behavior of harbor porpoises, a harbor porpoise in a large pool was exposed to simulated low- and mid-frequency active sonar signals (series of 1-s duration frequency-modulated sweeps). Three sweep pairs were tested: (1) a 1 to 2 kHz up-sweep was compared with a 2 to 1 kHz down-sweep (both without harmonics) at a mean received sound pressure level (mean received SPL) of 114 dB re 1 μPa; (2) a 1 to 2 kHz up-sweep was compared with a 2 to 1 kHz down-sweep (both with harmonics; mean received SPL: 123 dB re 1 μPa); and (3) a 6 to 7 kHz up-sweep was compared with a 7 to 6 kHz down-sweep (both without harmonics; mean SPL: 107 dB re 1 μPa). For each sweep pair, the level was chosen during a pretest session with the intention that the harbor porpoise would respond to the sounds by moving away from the projector and surfacing more often (i.e., he would show a change in behavior).

The study consists of three separate parts, so only a comparison within sweep pairs could be made and not between sweep pairs. For the 1 to 2 kHz sweeps with harmonics, the harbor porpoise swam further away from the sound source in response to the up-sweeps than to the down-sweeps. For the other two sweep pairs, sweep type (up-sweep or down-sweep) caused no significant difference in the harbor porpoise's response. Thus, to allow the evaluation of potential effects of sonar sounds on harbor porpoises, sonar signal measurements should include the harmonics. For simulated naval sonar sounds with fundamental frequencies in the 1 to 2 kHz range containing harmonics, using down-sweeps appears to affect harbor porpoise behavior less than using up-sweeps.

Key Words: acoustics, anthropogenic noise, behavior, response, sonar, sweeps, odontocete, navy, underwater noise

Introduction

Knowledge of the hearing systems and the behavior in response to sounds of many marine mammals is limited, but sound is particularly important for them as it is used as a means of orientation; communication; and to locate prey, conspecifics, and predators (Richardson et al., 1995). Therefore, many marine mammal species are likely to be disturbed by noise in their environment. Thus, noise in the oceans caused by human activities may have negative physiological, auditory, and behavioral effects on marine fauna.

The contribution of anthropogenic noise to the background noise in the oceans has increased steadily during the last century. Navies worldwide have caused part of this increase by employing shipping, explosions during exercises and destruction of ammunition, and sonar systems. Active sonar, used by navies to detect submarines, produces high-level underwater sounds (Funnell, 2009). To augment the resolution of sonar, frequency-swept sound signals are often used (Atherton, 2011): either up-sweeps (in which the frequency-increases over time) or down-sweeps (in which the frequency decreases over time).

Currently, many European navies use Mid-frequency Active Sonar systems (MFAS, with sweeps in the 5 to 10 kHz band) (Funnell, 2009). The signals are usually of short duration (up to 1.2 s), and the inter-pulse interval (usually between 10 and 30 s) is set by the sonar operator depending on the expected distance of the target submarine (Funnell, 2009) and the search mode. During the next 5 to 10 y, increasing use will be made by surface ships of Low Frequency Active Sonar systems (LFAS, with sweeps in the ~ 0.5 to 2 kHz band). Systems are under development in France, Germany, the UK, and the United States to detect submarines at greater distances (Funnell, 2009). The signal duration of these new systems can be up to several seconds, and the inter-pulse interval is expected to be around 30 s. Inter-pulse interval depends on water depth. The total duty cycle of multi-ship naval exercises in which several sonar systems are used can be high. In addition, naval sonar systems may produce signals with harmonics or side-bands—byproducts which are not used for detection purposes.

The effect of MFAS and LFAS signals on the behavior of killer whales (*Orcinus orca*), long-finned pilot whales (*Globicephala melas)*, and sperm whales (*Physeter macrocephalus*) has been studied in the wild (Miller et al., 2012). The most severe responses observed (i.e., the most likely to affect vital rates) included temporary separation of a calf from its group, cessation of feeding or resting, and avoidance movements that continued after the sonar system stopped transmitting. Responses started at lower sound pressure levels (SPLs) for killer whales, and responses of killer whales and sperm whales were more severe than those of long-finned pilot whales.

The effects of sonar sounds on the hearing and responses of another odontocete, the harbor porpoise (*Phocoena phocoena*), are of particular interest because the species has a wide distribution area in the Northern Hemisphere, one of the most acute hearing systems so far quantified in a marine mammal species, and functional hearing over a very wide frequency range. Harbor porpoises are relatively easily deterred by anthropogenic underwater noises such as those produced by ships (Amundin & Amundin, 1973; Polacheck & Thorpe, 1990), acoustic alarms to prevent unwanted bycatch in gillnet fisheries (Kastelein et al., 1997; Laake et al., 1998; Culik et al., 2001; Johnston, 2002; Olesiuk et al., 2002; Teilmann et al., 2006), operational offshore wind turbines (Koschinski et al., 2003), construction of offshore wind farms (Carstensen et al., 2006; Tougaard et al., 2009), and underwater data communication systems (Kastelein et al., 2005). Avoidance threshold levels of harbor porpoises have been determined for noise bands around 12 kHz (Kastelein et al., 2005), a continuous 50 kHz tone, and continuous and pulsed 70 and 120 kHz tones (Kastelein et al., 2008a, 2008b). The signal's temporal and spectral content, and the received level (RL), play important roles in the effect a sound has on the behavior of harbor porpoises; the context in which the sound is perceived (i.e., the behavior of the animal during exposure, whether it is in captivity or free-ranging) is also important.

The effects of MFAS and LFAS sweeps on harbor porpoises are expected to differ as the sensation levels for the signals are different. The hearing threshold difference at the fundamental frequency between the two signals is approximately 25 dB (see Kastelein et al., 2010). The presence or absence of harmonics in the signal has an effect on the broadband hearing threshold, especially for signals with low-frequency fundamentals (Kastelein et al., 2011a). Up to ~140 kHz, the hearing sensitivity of harbor porpoises increases with frequency (Kastelein et al., 2002, 2010); a similar increase in sensitivity with frequency exists for the equal-loudness contours of this species (Wensveen et al., 2014). This means that harmonic frequencies can be perceived to be louder than the fundamental frequencies used in navy sonar systems and, thus, may affect harbor porpoise behavior more than fundamental frequencies.

So far, two papers on the effect of sweeps on harbor porpoise behavior have been published. Kastelein et al. (2011b) tested the effect of broadband-noise masking on the behavioral response of a harbor porpoise to 1-s duration 6 to 7 kHz sonar up-sweeps. Kastelein et al. (2012) determined which levels of single 1 to 2 kHz and 6 to 7 kHz up-sweeps and down-sweeps (the same sweeps as used in the present study) caused a startle response in a harbor porpoise in 50% of signal presentations. These two sweeps' frequency ranges fall within the frequency ranges of both the MFAS and LFAS systems used by European navies.

Up-sweeps sound like something approaching (because of their resemblance to changing sounds produced by approaching sound sources due to the Doppler effect), whereas down-sweeps sound like something moving away. In studies on a few species of terrestrial mammals, up-sweeps cause more arousal than down-sweeps (Gordon & Poeppel, 2001; O'Neill & Brimijoin, 2002). Maybe this is perceived universally among mammals. Therefore, the goal of this study was to investigate the difference in effects of sonar up-sweeps and down-sweeps, for signals with and without harmonics, produced at a high duty cycle, on the behavior of a harbor porpoise. The goal of the study was to compare behavioral reactions within sweep pairs and not between sweep pairs.

Methods

Study Animal

The male harbor porpoise (Identification Number: 02) used in this study had stranded on the Dutch coast (on the island of Texel) at the age of about 21 months and had been rehabilitated. During the study, he was ~3.5 y old, his body weight was ~33 kg, his body length was ~140 cm, and his girth at axilla was ~73 cm. His hearing was assumed to be representative of harbor porpoises his age; it was similar to that of two other young harbor porpoises (Kastelein et al., 2002, 2009, 2010).

Study Area
The study was conducted at the SEAMARCO Research Institute, The Netherlands. Its location is remote and quiet, which is why it was selected for this acoustic research. The animal was kept alone in a pool complex specifically built for acoustic research, which consisted of an outdoor pool (12 × 8 m, 2 m deep; Figure 1) connected via a channel (4 × 3 m, 1.4 m deep) to an indoor pool (8 × 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 reflections of sound in the pool, the walls were covered with 3-cm thick coconut mats with their fibers embedded in 4-mm thick rubber (reducing reflections mainly above 25 kHz), and the bottom was covered with a 20-cm thick layer of sloping sand. The coconut mats reached up to 10 cm above the water level to reduce the splashing noise of waves. The water level was kept constant with skimmers. The seawater was pumped directly from the nearby Oosterschelde, a lagoon of the North Sea, into the open system; 80% recirculation through sand filters ensured year-round water clarity.

The water circulation system and aeration system for the biofilter were made as quiet as possible by mounting the "whisper" pumps on rubber mats and connecting them to the circulation pipes with flexible hoses. The average monthly water temperature varied during the year between 2° and 20° C; the salinity was around 34‰. There was no current in the pool during the experiments as the water circulation pump and the air pump of the adjacent biofilter were shut off 30 min before and during sessions. By the time a session started, no water flowed over the skimmers so that there was little or no flow noise.

The equipment used to produce the sound stimuli was housed out of sight of the study animal in a research cabin next to the pool (Figure 1).

Video Equipment
The animal's behavior was filmed from above by a camera (Conrad, Model 750940) with a wide-angle lens and a polarized filter to prevent saturation of the video image by glare from the water surface. The camera was mounted on a pole 9 m above the water surface on the northwestern side of the pool (Figure 1). The entire surface of the pool was captured on the video image. The output of the camera was fed through a video multiplexer (MX-8-CSX), which added the time and date to the images. Thereafter, the output was digitized with an analog-to-digital converter (EZ Grabber, Vista version) and stored on the computer.

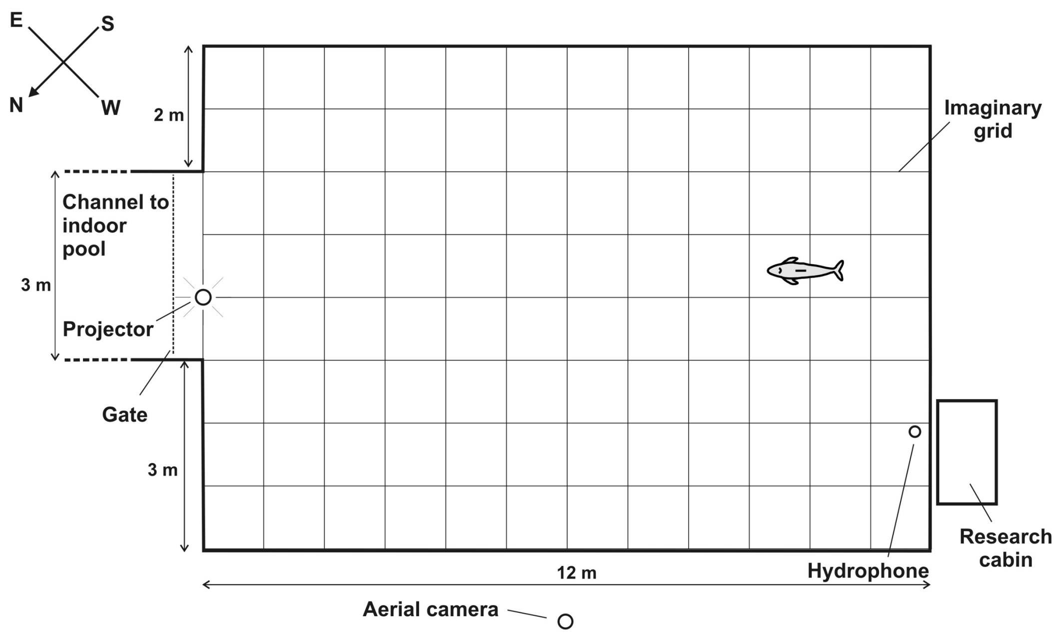

Figure 1. Top scale view of the study facility, showing the study animal, the location of the aerial camera, the underwater projector emitting the sweeps, and the listening hydrophone; also shown is the research cabin, which housed the equipment and the operator. The imaginary grid (1 m × 1 m), which was superimposed on the screen of the computer showing video recordings, served to identify the surfacing locations of the harbor porpoise (*Phocoena phocoena*).

Audio Equipment
Digitized test sounds (WAV files of sweeps; sample rate 88.2 kHz) were played by a laptop computer (Medion, Model MD96780), and the output went to an audio power amplifier (Velleman, Model HQ VPA2200MBN) before being transmitted. The sounds were projected via a cylindrical projector (EDO Western, Model 337) suspended 1 m below the water surface at the northeastern end of the pool near the entrance of the channel toward the indoor pool (Figure 1). This projector was chosen due to its omnidirectionality in the horizontal plane, which reduced the shadow effects in the corners of the pool. During test sessions, the output of the sound system to the projector was monitored with a digital storage oscilloscope (Tektronix, Model 2201) and a voltmeter (Agilent, Model 34401A).

The audio part of the background noise and the test sounds were recorded via a hydrophone (Labforce, Model 90.02.01) and a custom-built pre-amplifier. The output of the pre-amplifier was digitized via the analog-to-digital converter and recorded with the video images on the computer. The output was also fed to an amplified speaker so that the operator in the research cabin could monitor the background noise and the test sounds during sessions.

Test Stimuli
Three pairs of hyperbolic frequency-modulated sweeps were used to test the behavioral response of the harbor porpoise (see Kastelein et al., 2012, for characteristics). Each pair consisted of two sweep types: one up-sweep and one down-sweep. All sweeps had durations of 1 s, including 50 ms "fade in" and "fade out" times. The frequency ranges and source levels (see further on) of the up-sweeps and down-sweeps within each pair were identical.

Because they fall within the frequency range of the signals of new generation LFAS systems, 1 to 2 kHz up-sweeps and 2 to 1 kHz down-sweeps were selected; and 6 to 7 kHz up-sweeps and 7 to 6 kHz down-sweeps were selected because they are in the same frequency range as the signals used in existing tactical MFAS systems. Sweeps are used in naval sonar systems to reduce standing waves and thus produce more stable SPLs. The harbor porpoise's response was tested for the following three sweep pairs:

1. 1 to 2 kHz up-sweeps and down-sweeps (without harmonics)
2. 1 to 2 kHz up-sweeps and down-sweeps (with strong harmonics)
3. 6 to 7 kHz up-sweeps and down-sweeps (without harmonics)

Sounds were transmitted in sequences, with random inter-sweep times of between 3 and 7 s. The total sequence duration was 30 min (duty cycle: 19%). Random inter-sweep times were chosen to reduce habituation of the harbor porpoise to the sounds.

Acoustic Measurements
The test signals were recorded in the outdoor pool while the study animal was not present. The recording and analysis equipment consisted of three Brüel & Kjær (B&K) 8101 hydrophones with custom-built power supplies, a B&K PULSE 3560 D multichannel high-frequency analyser, and a laptop computer with B&K PULSE software *Labshop*, Version 12.1. The system was calibrated with a B&K 4223 pistonphone.

Acoustic Characterization of the Sweep Signals—The recorded signals were characterized in terms of broadband (20 Hz to 200 kHz) SPL (dB re 1 µPa), which was derived from the 90% energy flux density and the corresponding 90% time duration (t_{90} in s) (Madsen, 2005). The duration of the sweep (t_{90} in s) was defined as the time between the moments when the cumulative sound exposure (the integrated broadband sound pressure squared) reached 5 and 95% of the total exposure (i.e., the duration contained 90% of the total energy in the sweep [Madsen, 2005]). For the sweep signals used in this study, the t_{90} was 0.8 (± 0.1) s. The ⅓-octave band spectra of the SPL were determined via digital filtering of the time signal (t_{90}). The source level of the sweeps, characterized by the SPL measured by the hydrophone at 1 m from the projector, is denoted as SPL (1 m). Because the pool was highly reverberant, the SPL (1 m) is not an actual source level but a measure influenced by the acoustics of the pool, which is used as representative of the source level.

Determination of the Levels Used in the Tests—During a pretest, the acoustic levels needed for the tests were determined for the up-sweeps as the majority of naval sonar systems use up-sweeps. The SPL was increased during a number of sessions. The behavior of the harbor porpoise was carefully monitored to make sure that the animal did not show severe responses that may have compromised its well-being. As a result of the pretests, the 1 to 2 kHz and 6 to 7 kHz sweeps without harmonics were presented at the highest level at which no harmonics occurred in the playback system (a clear response was elicited but no harm was caused to the harbor porpoise). The 1 to 2 kHz sweeps with strong harmonics were presented at a slightly higher level than the 1 to 2 kHz sweeps without harmonics in order to generate the strong harmonics in the playback system. This increase in level did not result in a level increase of the fundamental frequency. For the down-sweeps of each pair, the same level was used as for the up-sweeps. The broadband SPLs and the level of the second harmonic of the sweep signals used are shown in Table 1. The energy in the fundamental frequency of the 1 to 2 kHz sweeps without harmonics (Figure 2a) equaled the energy in the fundamental frequency of the 1 to 2 kHz sweeps with harmonics (Figure 2b), and the energy in the fundamental frequency of the 6 to 7 kHz sweeps (Figure 2c) was approximately equal to the energy in the ⅓-octave band centered at 6.3 kHz of the 1 to 2 kHz sweeps with harmonics. The 6 to 7 kHz sweeps without harmonics did exhibit very weak harmonics close to the time-variable background noise (Figure 2c) but are referred to here for simplicity as "without harmonics."

SPL Distribution Measurements—To determine the distribution of sound in the pool, the SPL (20 Hz to 32 kHz) for each test sound was measured at 77 locations (on a horizontal grid of 1 m × 1 m) at three depths per location (0.5, 1.0, and 1.5 m below the water surface). Thus 231 SPL measurements were made for each of the three sweep pairs (Figure 3). The SPL distribution of the up-sweep and down-sweep in each pair was identical (i.e., maximum difference per location in the pool: 1 dB; maximum difference of mean SPL of each of the three horizontal planes: 0.1 dB).

Experimental Procedures

The projector was positioned in the pool (Figure 1) 30 min before each session started. Each session consisted of a 30-min baseline period (no sound emission) followed immediately by a 30-min test period (sound emission). One session was conducted per day, normally 5 d/wk. During the tests, personnel stayed at least 10 m away from the pool to ensure that nothing could distract the harbor porpoise.

One sweep type (i.e., the up-sweep or down-sweep of one pair only) was tested per session. Twelve sessions per sweep type were conducted (72 sessions in total). To ensure low and fairly constant ambient noise, tests were not carried out during rainfall or when wind forces were above Beaufort 4. The sessions of each of the six sweep types were presented in random order of up-sweeps and down-sweeps during the approximately 6-wk period in which a sweep pair was tested. The three sweep pairs were tested successively in the following order: (1) 1 to 2 kHz with harmonics, (2) 1 to 2 kHz without harmonics, and (3) 6 to 7 kHz without harmonics. The study was conducted from September 2008 until January 2009 and from August until October 2009.

Response Parameters and Behavioral Data Recording

Two objective behavioral parameters were used to quantify the harbor porpoise's responses to the sweeps: (1) the average distance between his surfacing locations in the pool and the projector, and (2) his number of surfacings per unit time (i.e., approximately his number of respirations; he occasionally breathed more than once while floating at the surface). Both parameters were quantified as the value for each test period minus the value for the corresponding baseline period.

The relative distance between the mean surfacing location and the projector was quantified to determine whether the harbor porpoise responded to the sounds by swimming away from the sound source. This was done as follows: from video camera recordings, the locations where the harbor porpoise surfaced during the baseline and test periods were identified on a grid superimposed on the computer screen. The grid corresponded to a pool grid of 1 m × 1 m and was made by superimposing lines on the screen to connect physical 1 m markers on the pool's sides (Figure 1). The center point of the grid square of each surfacing was used to calculate the distance of the harbor porpoise's surfacing location to the projector via triangulation. Depth was not taken into account

Table 1. The broadband SPL (1 m) in dB re 1 μPa of the three sweep pairs, the level of the second harmonic in relation to the fundamental frequency, and the mean received (dB-average) SPL over all 231 measurement positions in the pool, with standard deviations (SD); all sweeps had a hyperbolic frequency modulation, 50 ms "fade in" and "fade out" times, a total duration of 1 s ($t_{90} \approx 0.8$ s), and a random inter-sweep time of between 3 and 7 s (duty cycle: 19%).

Sweep pair	SPL (1 m) broadband SPL (dB re 1 μPa)	Mean received broadband SPL ± SD in pool (dB re 1 μPa)	Level of second harmonic (dB)
1-2 kHz without harmonics	122 (122*)	114 ± 3	-42
1-2 kHz with harmonics	128 (122*)	123 ± 2	-6
6-7 kHz without harmonics	113 (113*)	107 ± 3	-17

* SPL (at 1 m) of the signal when band-filtered in the sweep frequency range only

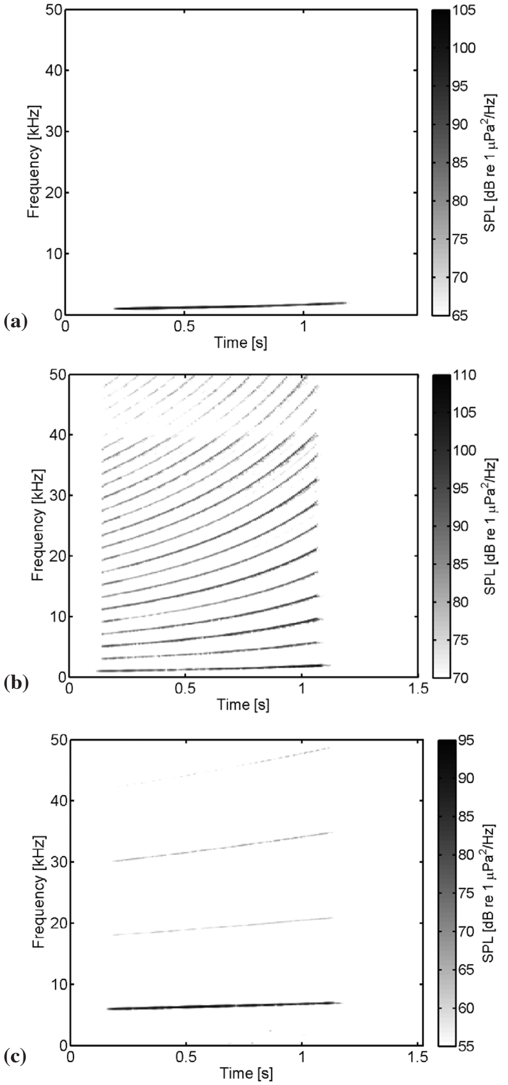

Figure 2. Spectrograms of (a) 1 to 2 kHz up-sweep without harmonics (broadband SPL [1 m] = 122 dB re 1 μPa), (b) 1 to 2 kHz up-sweep with harmonics (broadband SPL [1 m] = 128 dB re 1 μPa), and (c) 6 to 7 kHz up-sweep without harmonics (broadband SPL [1 m] = 113 dB re 1 μPa); the frequency range in this figure is limited to 50 kHz to keep the fundamental sweeps visible and the harmonics well separated.

because no major differences in SPL occurred between the three depths at each location. During test sessions, the water was always clear. When light conditions were such that the bottom of the pool was visible and the harbor porpoise could be seen well below the water surface, his surfacing locations were related to his general swimming area. Hence, the surfacing locations provided a good indication of the harbor porpoise's general swimming area.

Analysis

Data were collected from the video recordings by one person to ensure standard methods. A *t* test was carried out to compare the harbor porpoise's response to up-sweeps with that to down-sweeps for each of the three sweep pairs, separately for relative distance to the projector and relative numbers of surfacings (6 tests in total; $n = 12$ for each). Data conformed to the assumptions of tests used, and the level of significance was 5% (Zar, 1999).

Results

During baseline periods, the harbor porpoise usually swam large clockwise ovals in the pool. His mean distance from the projector was similar in all 72 baseline periods (mean ± SD = 6.1 ± 1.0 m). On average, the harbor porpoise surfaced 84 times (± 23) during each 30-min period, and he showed a regular dive pattern consisting of long dives alternated with shorter dives.

During test periods, the harbor porpoise generally swam faster and further away from the projector, surfaced more often, and showed a less regular dive pattern. However, the response within each of the three sweep pairs was not identical as detailed below.

The effect of 1 to 2 kHz sweeps without harmonics (mean received SPL: 114 dB re 1μPa) was similar for up-sweeps and for down-sweeps (relative distance from the projector: $t = -1.26$, $p = 0.224$, $df = 19$; relative number of surfacings: $t = 1.86$, $p = 0.077$, $df = 20$; Figures 4a & 4b). At the level used, the effect of the 1 to 2 kHz sweeps without harmonics was relatively weak as evidenced by the low mean values for relative distance and relative number of surfacings (Figures 4a & 4b). After each session, the animal's behavior immediately returned to normal.

The effect of 1 to 2 kHz sweeps with harmonics (mean received SPL: 123 dB re 1μPa), as quantified by the relative distance from the projector, was significantly greater for up-sweeps than for down-sweeps ($t = -4.93$, $p = 0.000$, $df = 17$; Figure 4c), but the relative number of surfacings was similar for up-sweeps and for down-sweeps ($t = 1.01$, $p = 0.325$, $df = 21$; Figure 4d). At the level used, the effect of the 1 to 2 kHz sweeps with harmonics was moderate as evidenced by the moderately high mean values for relative distance and relative number of surfacings (Figures 4c & 4d). After each session, the animal's behavior immediately returned to normal.

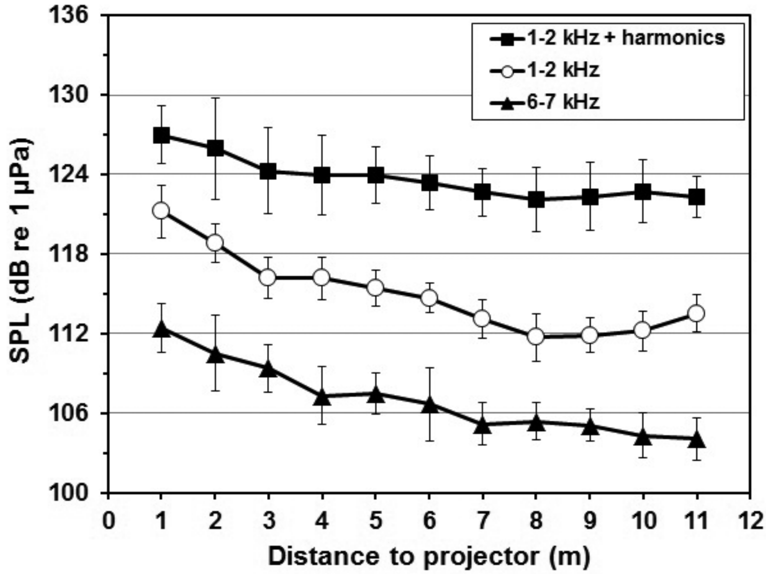

Figure 3. The mean SPL (in dB re 1 μPa; n = 231) of the three up-sweeps as a function of the linear distance from the measurement point to the projector; the SPL was not affected by hydrophone depth, so SPLs for the three depths are averaged for each sweep. In the vicinity of the projector, the direct field of the source dominated the reverberant field so that a gradient occurred up to approximately 7 m from the projector. Error bars represent SDs. The SPL distribution of the up-sweep and down-sweep in each pair was identical.

The effect of 6 to 7 kHz sweeps without harmonics (mean received SPL: 107 dB re 1μPa), as quantified by the relative distance from the projector and the relative number of respirations, was similar for up-sweeps and for down-sweeps (relative distance from the projector: $t = 0.80$, $p = 0.432$, $df = 21$; relative number of surfacings: $t = 0.27$, $p = 0.792$, $df = 21$; Figures 4e & 4f). At the level used, the effect of the 6 to 7 kHz sweeps without harmonics was strong as evidenced by the high mean values for relative distance and relative number of surfacings (Figures 4e & 4f). Still, after each session, the animal's behavior returned to normal immediately.

Discussion

Evaluation

It cannot be said whether the response of the single study animal was representative for its species. However, the study animal's hearing was representative of that of harbor porpoises of his age; it was very similar to the hearing of another male harbor porpoise of the same age (Kastelein et al., 2009). The three sweep pairs were tested one after the other, so an order effect may have occurred, and the levels at which the sweeps were produced were different for each sweep pair and were only chosen to elicit a response, and not a specific level of response. Only the responses to the up-sweeps and down-sweeps within each pair, which were tested in random order and had identical levels, were therefore compared statistically.

After each session, the animal's behavior returned to normal immediately. He cooperated in psycho-acoustic tests only minutes after the sweeps had ceased. Similar quick returns to baseline behavior after exposure to loud sounds were seen in previous acoustic alarm (pinger) studies with harbor porpoises (Kastelein et al., 2000, 2001, 2006, 2008a, 2008b) and were the reason for not including posttest observation periods in the present study as was done in the pinger study by Kastelein et al. (2000).

Responses of marine mammals to sonar sounds are probably species- and context-specific (Southall et al., 2007). For example, in response to sonar sounds broadly similar to those used in the present study (but with different frequencies, signal durations, complexity of the frequency sweeps, and repetition rates), beaked whales (*Ziphiidae*) became silent and swam away from the sound source, while pilot whales (*Globicephalus* sp.) increased their vocalizations and showed no apparent avoidance behavior (Tyack et al., 2011). Watkins et al. (1985) showed that sperm whales stopped echolocating in response to naval sonar signals, whereas Rendell & Gordon (1999) showed an increase in vocalization in long-finned pilot whales. The distance between animals and the sound source may also play a role in how they react to sounds.

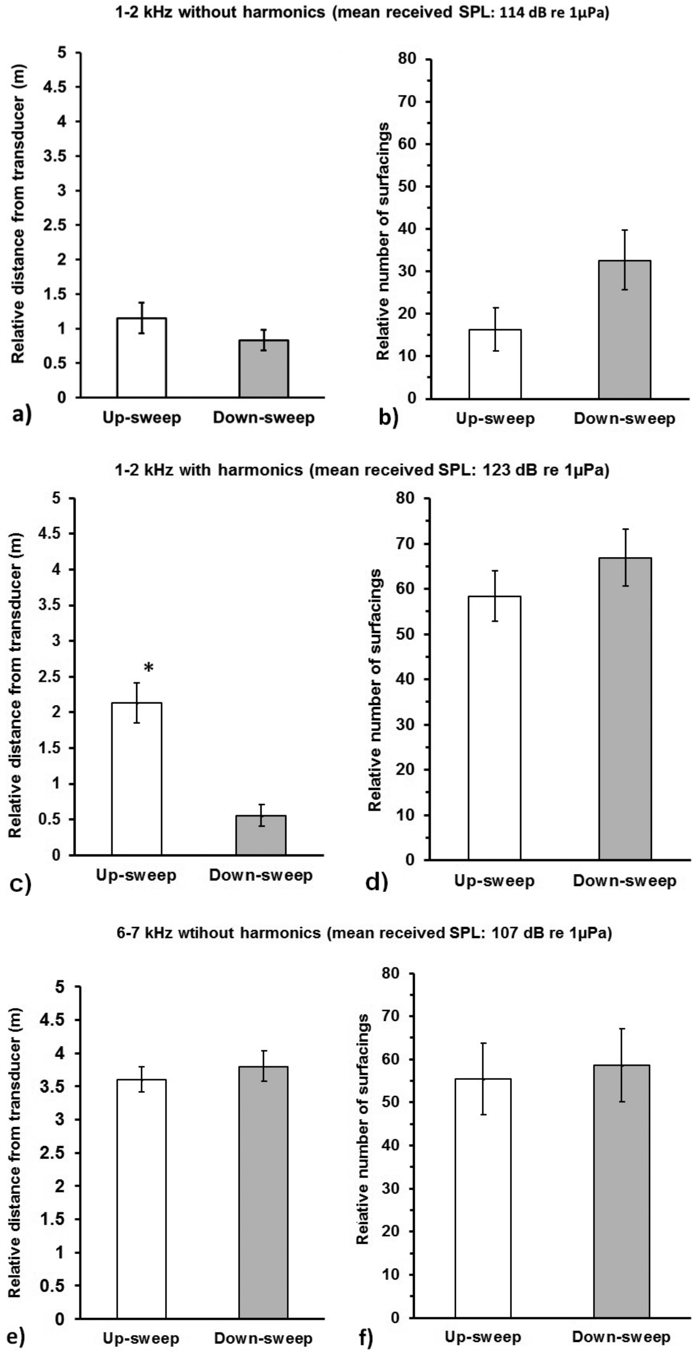

Figure 4. Means and standard errors (n = 12) for relative distance from the transducer and relative number of surfacings in response to up-sweeps and down-sweeps; values of zero would indicate no difference between baseline and test periods. Positive values indicate that distances from the projector and numbers of surfacings were higher during test periods than during baseline periods. 1 to 2 kHz sweeps without harmonics: a) relative distance from the projector, and b) relative number of surfacings; 1 to 2 kHz sweeps with harmonics: c) relative distance from the projector—the response to up-sweeps was significantly greater than that to down-sweeps (*), and d) relative number of surfacings; 6 to 7 kHz sweeps without harmonics: e) relative distance from the projector, and f) relative number of surfacings. The total sequence duration was 30 min (duty cycle: 19%).

DeRuiter et al. (2013) reported that Cuvier's beaked whales (*Ziphius cavirostris*) responded strongly to playbacks at low received SPLs (89 to 127 dB re 1 μPa): after ceasing normal fluking and echolocation, they swam rapidly, silently away, extending both dive duration and subsequent non-foraging interval. Distant sonar exercises (Received SPLs: 78 to 106 dB re 1 μPa) did not elicit such responses, suggesting that context may moderate reactions.

The responses of the harbor porpoise in the present study, if observed in free-ranging animals, would be classed as 3 to 4 on the severity scale for ranking observed behavioral responses (range 1 through 9) presented by Southall et al. (2007). The effects seen in the present study occurred under very low background noise conditions. Under higher background noise conditions, effects may be less severe. A study of behavioral responses of harbor porpoises to 6 to 7 kHz sonar sounds under different ambient noise conditions showed that responses decrease as ambient noise increases for equal SPL sonar sound exposures (Kastelein et al., 2011b).

Effect of Up-Sweeps and Down-Sweeps

The present study shows that for the 1 to 2 kHz sweeps with strong harmonics, up-sweeps were more aversive to the harbor porpoise than down-sweeps. There are at least two possible explanations for this. First, up-sweeps with strong harmonics resemble more closely the social calls (which also consist of up-sweeps with harmonics) of killer whales (Miller et al., 2004, 2007; Brown et al., 2006), the main predators of harbor porpoises, than down-sweeps in the same frequency band. Second, up-sweeps sound like something approaching (because of their resemblance to perceived changes in approaching sounds due to the Doppler effect), whereas down-sweeps sound like something moving away. If this is perceived universally among mammals (Gordon & Poeppel, 2001; O'Neill & Brimijoin, 2002), up-sweeps may be more aversive because they are perceived as approaching, and harmonics may increase this perception.

Kastelein et al. (2012) recorded startle responses to single presentations of the sweeps used in the present study. No difference was found between the 50% startle response threshold levels for the up-sweeps and down-sweeps. Startle responses were very quick and usually occurred within the signal presentation. This suggests that the animal is not interpreting the signal but, rather, is showing a reflex response. In the present study, the signals were produced at a 19% duty cycle for 30 min. This may explain the difference in reaction to the 1 to 2 kHz up-sweeps and down-sweeps with strong harmonics in the two studies.

Recommendations for Tactical Naval Sonar Systems

If the same sonar information can be derived from up-sweeps and down-sweeps, then in order to minimize their effect on harbor porpoise behavior (assuming the response of the harbor porpoise in the present study was representative), future tactical sonar systems in the 1 to 2 kHz frequency range with harmonics should be designed to produce only down-sweeps.

Sounds with harmonics are often produced in tactical naval sonar systems, but the energy in the harmonics is mainly a byproduct of sound generation and is not used to derive information. Harbor porpoises are more sensitive to high-frequency sound, so tactical sonar systems which produce no harmonics, or harmonics with little energy, probably cause less avoidance behavior than those which produce harmonics. The aural character of sounds with harmonics depends on the level of each harmonic relative to the fundamental. Level differences of harmonics depend on the source level of operational naval sonar systems and on the distance between the animal and the sound source due to frequency-dependent differences in absorption. In all future studies of the impact of naval sonar sweeps on marine mammals, the spectral content of signals should be described in detail to allow the prediction of harbor porpoise reactions to the sonar sounds.

The results of the present study, in combination with the results of Kastelein et al. (2012), suggest that naval sonar systems producing signals in the 1 to 2 kHz range without harmonics could have higher source levels than those producing signals in the 6 to 7 kHz range without harmonics, with similar effects on harbor porpoise behavior.

Acknowledgments

We thank Lean Hoek for managing the students and the daily schedule to allow time for the study sessions, for her help with the data collection, and for her constructive comments on this manuscript. We thank Jesse Dijkhuizen and Tess van der Drift for their help with the data recording. We thank Rob Triesscheijn for making most of the figures, and Bert Meijering (Topsy Baits) for providing space for the SEAMARCO Research Institute. Erwin Jansen (TNO) did the acoustic measurements and made some of the figures. We also thank Christ de Jong (TNO) and Wim Verboom (JunoBioacoustics) for their valuable constructive comments on this manuscript, Arie Smink for constructing some of the electronic equipment and for maintaining it, and Hans Heiligenberg and Raymond van Elst (Royal Netherlands Navy) for their advice. Funding for this project was obtained from The Netherlands Ministry of Defense (contracts "WO Bruinvissen 235-06-0003-01" and "WO Geluidsduur Zeezoogdieren 235-08-6006-01"). We thank Erik van Arkel, Vincent Gales, and Ronald de Rooij (DRMV, Netherlands Ministry of Defense), and René Dekeling and Frans Jansen (Royal Netherlands Navy) for making the funding possible. The harbor porpoise was tested under authorization of the Netherlands Ministry of Economic Affairs, Department of Nature Management, with Endangered Species Permit FF/75A/2009/039. We thank Jan van Spaandonk (Netherlands Ministry of Economic Affairs) for his assistance in making the harbor porpoise available for this project.

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