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Behavioral Responses of Harbor Seals (*Phoca vitulina*) to FaunaGuard Seal Module Sounds at Two Background Noise Levels

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Abstract

To prevent permanent hearing impairment in seals, SEAMARCO and Van Oord Dredging and Marine Contractors have developed the FaunaGuard Seal Module (FG-SM), which is intended to deter seals to safe distances from high-amplitude impulsive sound sources such as offshore pile driving operations. As a first step towards testing and validating the FG-SM, a study with captive harbor seals is presented. The effects of 16 sounds (200 Hz to 20 kHz, with random inter-sound intervals of 3 to 10 s, mean interval 6.5 s, and duty cycle ~60%) produced by the FG-SM on the behavior of two harbor seals were quantified in a pool. The overall behavioral response threshold for these sounds was determined by transmitting the sounds at four sound pressure levels (SPLs) at two background noise levels resembling those occurring during Beaufort Sea States 0 and 4. Behavioral responses ranged from no reaction to increased time spent with the head above the water surface, more frequent hauling out, and increased numbers of jumps. The seals differed in their responses to the sounds: whereas seal 01 increased the time she spent with her head above the water surface as the SPL increased, seal 02 hauled out more often. Based on "jump" behaviors specifically, the mean received behavioral threshold SPL of the two seals in both background noise conditions appeared to be between 136 and 148 dB re 1 µPa (for the effect calculation, 142 dB re 1 µPa was used). No effect of the ambient noise level was observed; the level of the ambient noise at both Sea States was too low to mask the sounds of the FG-SM at the average levels the animals were exposed to in the pool. Based on the source level of the FG-SM, the mean behavioral response threshold SPL found in the present study for jumps, and two generic propagation models, the deterring effect range of the FG-SM is estimated to vary between 100 m (propagation model: 20log R) and 500 m (propagation model: 15log R). In most cases in the shallow North Sea, permanent hearing threshold shift (PTS) in harbor seals would be prevented if they moved 100 to 200 m away from the source of pile driving sounds, and, thus, the FG-SM is considered a good mitigation device.

Key Words: ADD (Acoustic Deterrent Device), AHD (Acoustic Harassment Device), and AMD (Acoustic Mitigation Device). acoustic disturbance, anthropogenic noise, FaunaGuard Seal Module, offshore pile driving, Phocid, harbor seal, *Phoca vitilina*, PTS

Introduction

Anthropogenic use of the marine environment is increasing and involves, among other things, dredging and construction activities for marine infrastructure developments, sand mining, and construction and operation of oil platforms and wind farms. There is particular concern about the potentially harmful impact of loud, impulsive sounds on marine mammals (National Research Council [NRC], 2003). These sounds are produced by airguns during seismic surveys, by the detonation of ammunition, and by offshore percussive pile driving employed in construction. Impulsive sounds can lead to temporary or permanent hearing damage in marine mammals, or to flight reactions, that, in cetaceans, may result in stranding (Amoser & Ladich, 2003; Jepson et al., 2003; Smith et al., 2004; Brumm & Slabbekoorn, 2005). Acoustic Deterrent Devices (ADDs, also called acoustic harassment devices or pingers) can protect marine fauna from potentially harmful sound produced during anthropogenic activities by temporarily deterring the animals away from the zone of impact. Various sounds, produced at various duty cycles, are used. Many ADDs are available, but their effectiveness is rarely scientifically validated (Götz & Janik, 2015). As an alternative to existing approaches, SEAMARCO and Van Oord Dredging and Marine Contractors have developed the FaunaGuard, an ADD used to deter various marine fauna species safely and temporarily from marine construction sites by means of specialized underwater sounds. The effectivity of the FaunaGuard is being studied both in pools and at sea for porpoises, fish, turtles, and seals (Van der Meij et al., 2015).

The harbor seal (*Phoca vitulina*) is a marine mammal species that is widely distributed in the shallow coastal waters of the Northern Hemisphere. Its hearing may be impaired by high-amplitude impulsive anthropogenic sounds. The hearing of harbor seals is sensitive for low-frequency sounds (Kastelein et al., 2009a, 2009b, 2010; Reichmuth et al., 2013), so the sensation level (i.e., the difference between the level of a signal and the basic tonal 50% hearing threshold) of impulsive sounds for harbor seals is expected to be relatively high. Therefore, such sounds may cause temporary hearing threshold shifts (TTS) or permanent hearing threshold shifts (PTS) in harbor seals, even when the sounds are experienced at relatively low levels but for long durations (e.g., 124 dB re µPa for 4 h; Kastelein et al., 2012).

ADDs have been developed to prevent injury to harbor seals' hearing due to impulsive underwater sound caused by anthropogenic activities, and to avoid other human impacts such as collisions of seals with vessels' propellers. Several types of ADDs for harbor seals are commercially available. They were mostly developed from devices used to reduce predation by seals at marine aquaculture farms. SEAMARCO and Van Oord Dredging and Marine Contractors have developed the FaunaGuard Seal Module (FG-SM), which produces 16 sounds in the 200 Hz to 20 kHz range, based on biological knowledge of seal hearing, behavioral responses, and characteristics of acoustic equipment.

The goal of the present study was to determine whether the FG-SM's sounds can deter harbor seals far enough away from any offshore construction activity location to prevent injury and PTS. The aim was to establish a dose-response relationship for captive harbor seals experiencing sounds produced by the FG-SM. From this dose-response relationship, a behavioral response threshold sound pressure level (SPL) can be determined. By combining the threshold SPL with information on the source level of the FG-SM's sounds, the background noise level, and local propagation conditions, the extent of the area around a source of potentially harmful sounds from which harbor seals may be deterred can be estimated. The behavioral responses were measured at two background noise levels to study the effect of masking on the dose-response relationship of the seals to the sounds produced by the FG-SM.

Methods

Study Animals and Study Area

The study animals were two female harbor seals (ID numbers 01 and 02). They were both 10 y old during the study, and the body weight of each was approximately 62 kg. The seals had very similar hearing that was representative for harbor seals of their age (Kastelein et al., 2009a, 2009b, 2010). The harbor seals' hearing was tested in 2015 and had not changed since a previous study by Kastelein et al. (2010). They had also participated in a behavioral response hearing study similar to the present study but with signals around 25 kHz (Kastelein et al., 2015).

The study was conducted at the SEAMARCO Research Institute, The Netherlands, which is in a remote and quiet area specifically selected for acoustic research. The research was conducted in an outdoor pool (8 m × 7 m, 2 m deep) with three haul-out platforms (Figure 1). The pool was designed and constructed to be as quiet as possible (see Kastelein et al., 2009b). A research cabin next to the pool housed the audio/video equipment and the operator, who was out of sight of the seals.

Acoustics

The FG-SM consists of a sound generator, a power amplifier, and an ultrasound detector. The sounds produced by the FG-SM in normal operation were considered too loud to play safely in the pool, so two digitally controlled attenuators were added between the sound generator and the amplifier (Figure 2). Via an isolation transformer, the sounds were transmitted by an underwater transducer (Lubell – 916), the same transducer that is used in the FG-SM. The transducer was placed at the eastern corner of the pool at 1 m depth (Figure 1).

The FG-SM produces 16 sounds in the 200 Hz to 20 kHz frequency band (Figures 3 & 4; Table 1). The sounds are produced in succession at random intervals of between 3 and 10 s (mean interval 6.5 s). The average duty cycle of a sequence of 16 sounds is approximately 60%.

The harbor seals' responses to the sounds produced by the FG-SM were recorded at two background noise levels. One level was the low background noise level in the pool (with local wind speed ≤ Beaufort Sea State 4, no rain), which resembled noise levels associated with Beaufort Sea State 0 (abbreviated as SS 0). The other level resembled the noise level and spectrum associated with Beaufort Sea State 4 (abbreviated as SS 4; Knudsen et al., 1948; Figure 5). The output of the

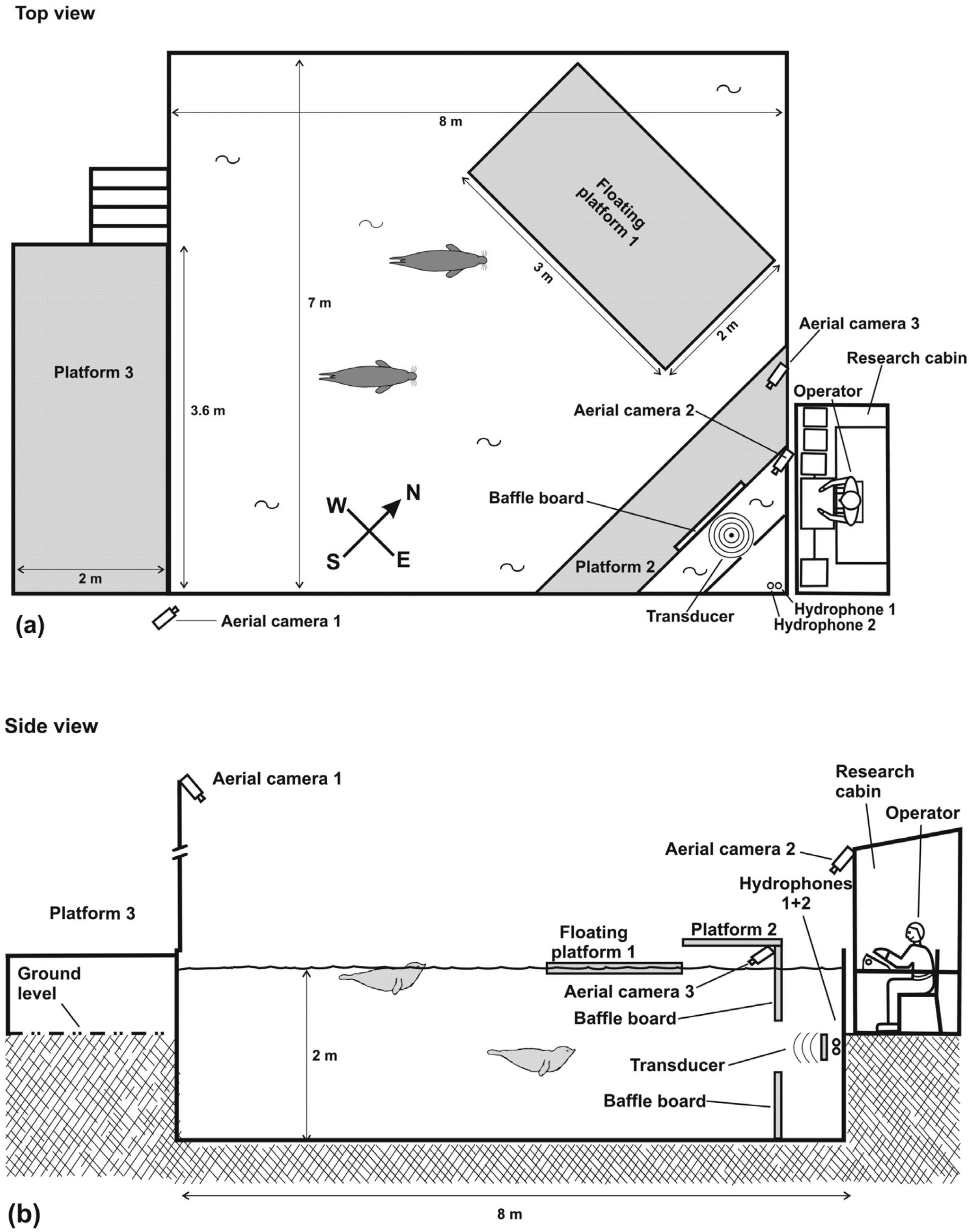

Figure 1. Top and ~45° side views, to scale, of the study facility, showing the study animals, the three aerial cameras, the underwater transducer emitting the FaunaGuard Seal Module's (FG-SM) sounds, the two listening hydrophones, and the three haul-out platforms. Also shown is the research cabin that housed the electronic equipment and the operator.

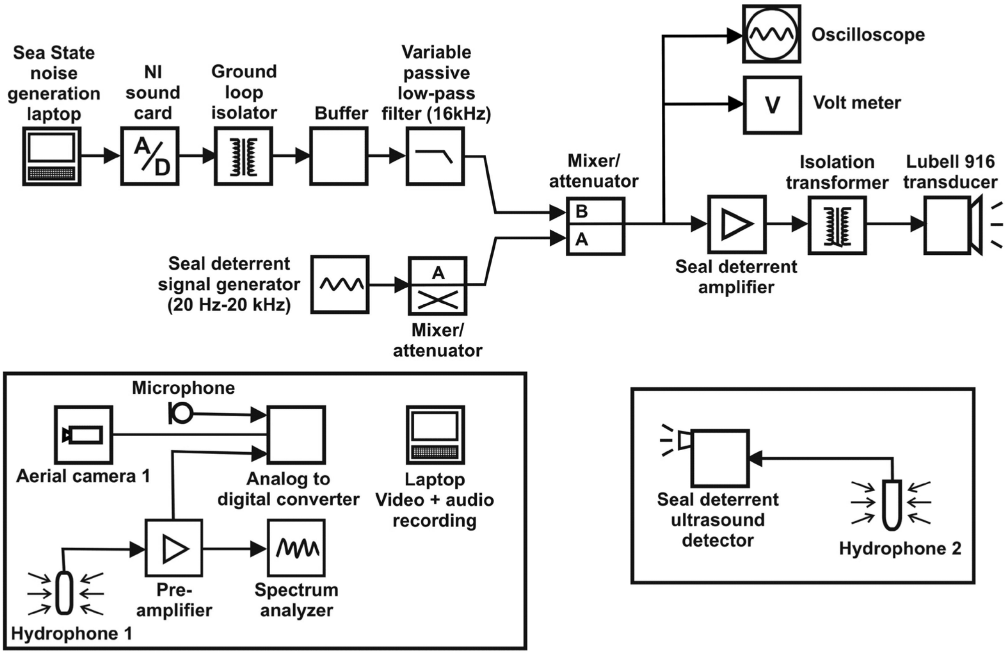

Figure 2. The audio set-up producing the FG-SM's sounds and the background noise designed to resemble the sound of Beaufort Sea State 4 (SS 4). Also shown are the video recording system and spectrum analyzer (bottom left) and the audio checking equipment for the operator (which is distinct from the audio measurement equipment; bottom right).

transducer producing the background noise was not linear, so the spectrum was composed using white noise (bandwidth: 100 Hz to 20 kHz), which was filtered in *Audacity* software to produce a WAV file specifically for the particular transducer used in the study. The background noise designed to resemble the noise level and spectrum associated with SS 4 was produced by playing the WAV file on a laptop computer (Acer Aspire 5750) with a program written in *LabVIEW* to an external data acquisition card (National Instruments – USB 6251), 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 custom-built buffer to a custom-built variable passive low-pass filter (set at 20 kHz), after which it went via a mixer/buffer to the power amplifier of the FG-SM, which drove the transducer (Lubell – 916) producing the FG-SM's sounds via the isolation transformer. The attenuation system was linear (within 1 dB) over the SPL range over which the FG-SM's sounds were produced in the study.

The output of the sound system to the power amplifier was monitored via an oscilloscope (Voltcraft – 632FG) and a voltmeter (Hewlett Packard – 3478A), and the sound transmitted into the water was checked with a hydrophone, a pre-amplifier, and a spectrum analyzer (Velleman – PCSU1000).

Acoustic Measurements

The sound levels in the pool were quantified while the FG-SM's sounds were being produced and the animals were not in the pool. The recording and analysis equipment consisted of three hydrophones (Bruel & Kjaer [B&K] – 8106) with a multichannel high-frequency analyzer (B&K PULSE – 3560 D) and a laptop computer with *Labshop*, Version 12.1 (B&K PULSE). The system was calibrated with a pistonphone (B&K – 4223). The sounds were not filtered, and the sample rate was set at 131,072 Hz.

The sound sequences were characterized in terms of their SPL. The SPL (dB re 1 μPa) was averaged over the duration of each sound; the analysis was done in the time domain. The duration (t_{90}) was determined as the time interval between the points when the cumulative sound exposure (the integrated broadband sound pressure squared) reached 5 and 95% of the total sound exposure—that is, the duration contained 90% of the total energy in the sound (Madsen, 2005). The SPL (dB re 1 μPa) was determined from the power sum of ⅓ octave bands from 25 Hz to 40 kHz. The source level was determined from SPL measurements at 2 m from the sound source, and 6 dB

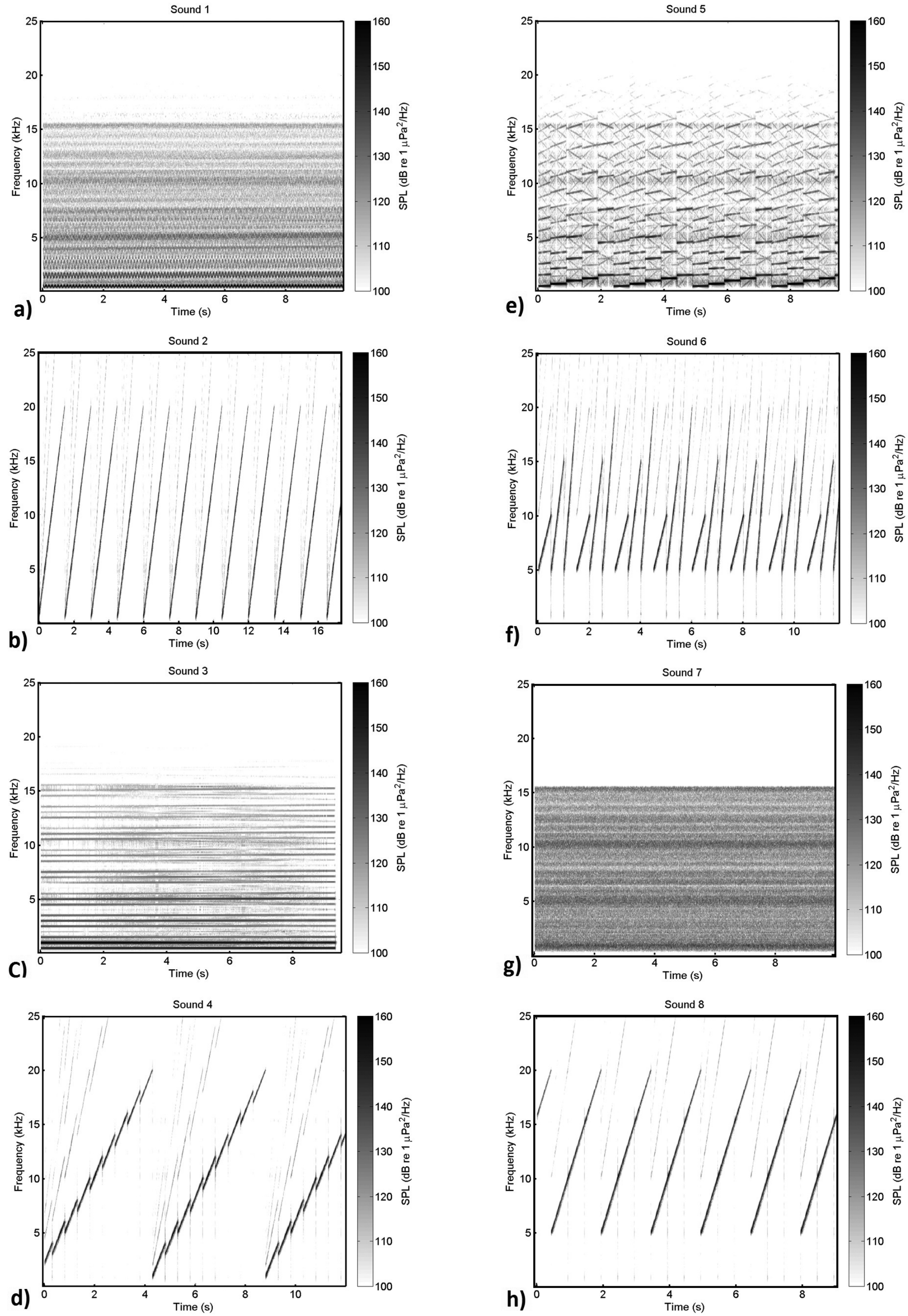

Figure 3a-h. Sonograms of the 16 sounds produced by the FG-SM to deter harbor seals (*Phoca vitulina*; see Table 1 for the description of the sounds)

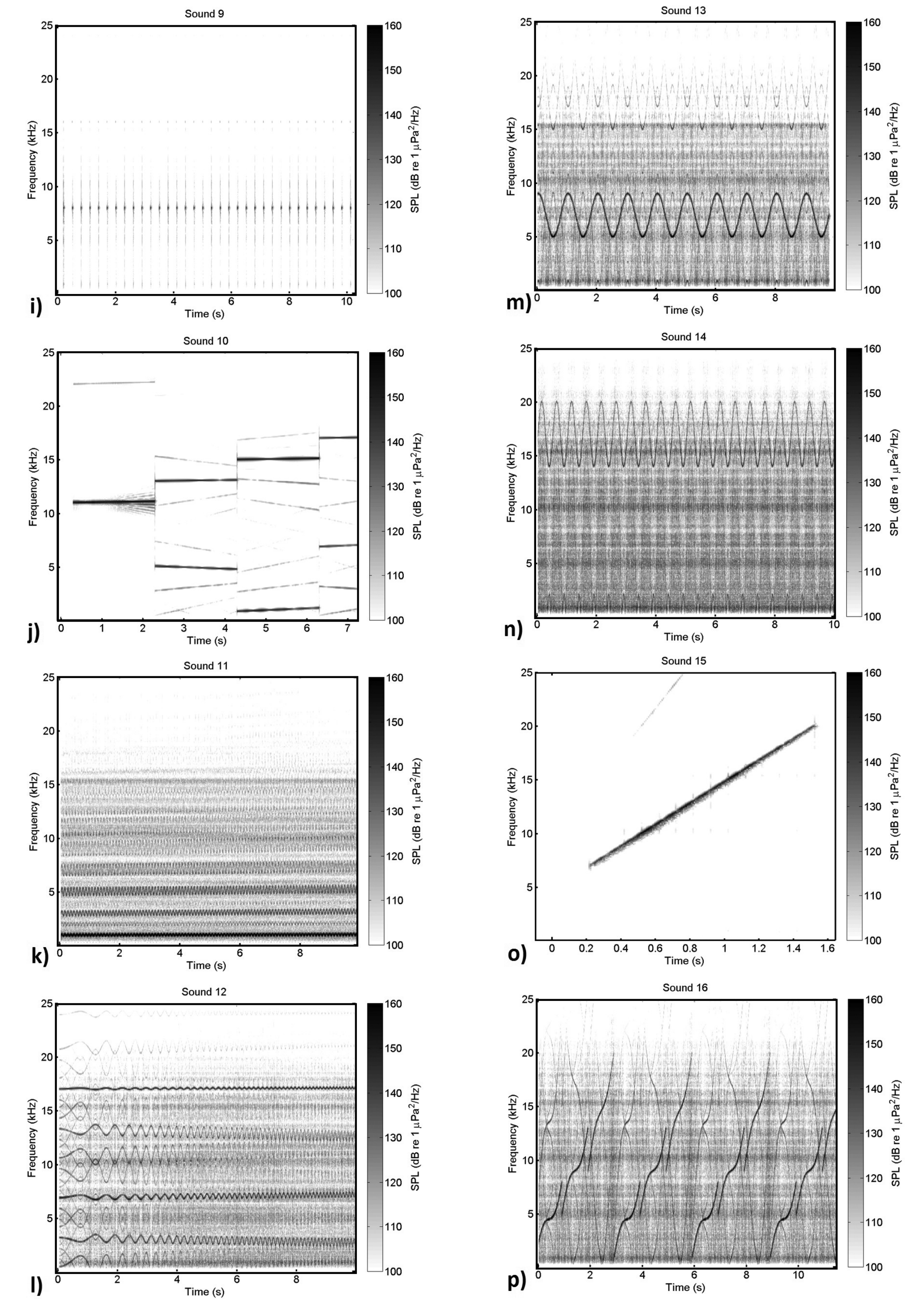

Figure 3i-p. Sonograms of the 16 sounds produced by the FG-SM to deter harbor seals (see Table 1 for the description of the sounds) was added to the measured values to calculate the source levels (Table 1).

Distribution of Deterrent Sounds

To determine the sound distribution in the 7 × 8 m, 2-m deep pool, the SPL for each sound type was measured under SS 0 conditions at nine locations in the horizontal plane. The pool was divided into nine rectangles (2.3 × 2.7 m), and the measurements were taken in the middle of each rectangle. Per location, the SPL was measured by three hydrophones at 0.5, 1.0, and 1.5 m below the water surface. Thus, the SPL of each sound produced by the FG-SM was measured at 27 locations in the pool. The reported SPLs were based on one recording per location. The mean SPL differences between the three depths (over all nine rectangles) varied slightly per signal type; the highest mean SPL was at -1 m deep (the depth of the transducer) and was 0 to 3 dB higher than the SPL at 0.5 m and 1.5 dB depth. The mean attenuation (over all 16 signals and all three depths per location; $n = 48$ for each mean) is shown in Figure 6. There was an SPL gradient of about 11 dB in the pool. The harbor seals used most of the pool and swam at all depths during the sessions, so the average SPL in the pool is used to describe the average SPL ($SPL_{av.rec.}$) received by the seals in this study.

Determination of the SPLs of the Playback Sequence

During a pilot study with a low background noise level in which the source level of the FG-SM's sounds was gradually increased in successive sessions, four SPLs were determined: (1) an $SPL_{av.rec.}$ which fell just below the threshold of behavioral change in the harbor seals, (2) the $SPL_{av.rec.}$ when both the animals hauled out, and (3) two intermediate $SPLs_{av\ rec.}$. These four $SPLs_{av.rec.}$, which each differed by 12 dB, were then tested under noise conditions resembling those of SS 0 and SS 4 (Table 2).

Video

The harbor seals' behavior was filmed by three aerial cameras (Conrad – 750940) with wide-angle lenses. Camera 1 was placed on a pole 6 m above the water surface in the southern corner of the pool (Figure 1). The entire surface of the pool was captured on the video image, except the areas behind and below platform 2 (platform 1 was floating). Camera 2 filmed the area behind the baffle board, and camera 3 filmed the area below platform 2. The output of camera 1 was digitized with an analog-to-digital converter (Smart Group – Zolid) and stored on a laptop computer (Medion – MD98110).

The audio part of the background noise and the test sounds were recorded via a custom-built hydrophone and a pre-amplifier (B&K – 2635). The output of the pre-amplifier was digitized via the analog-to-digital converter and recorded to a laptop computer in synchrony with the video images (Figure 2). The output was fed to an amplified loudspeaker so that the operator in the research cabin could monitor the background noise during sessions. Via a microphone, the operator added the date, time of day, session number, and SPL being tested to the video recording at the start of each session.

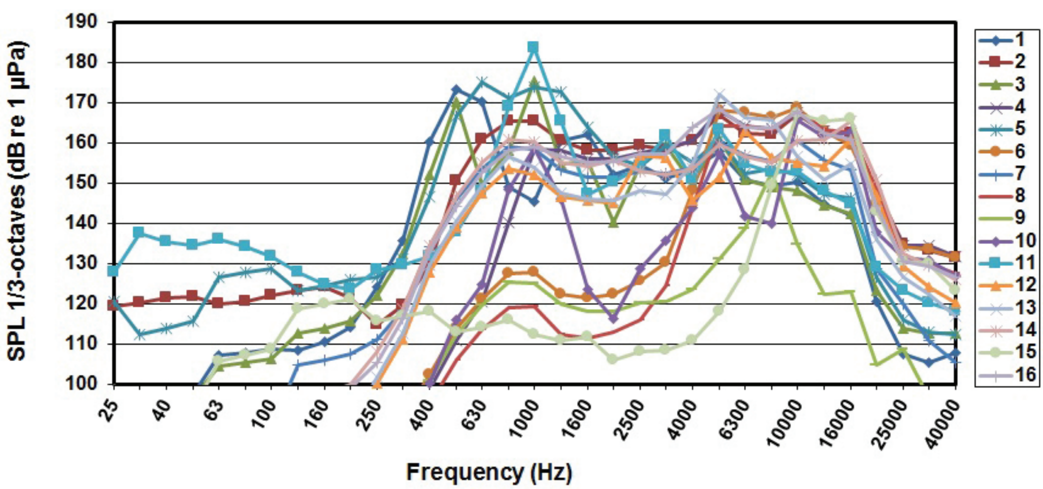

Figure 4. The spectra of the 16 sounds produced by the FG-SM; most of the energy is in the 200 Hz to 20 kHz frequency band. The numbers in the legend are the sound numbers (see also Figure 3 & Table 1 for information on the sounds).

Table 1. Details of the 16 sounds produced by the FaunaGuard Seal Module (FG-SM) and tested on two harbor seals (*Phoca vitulina*) in a pool. FM = frequency modulated and DC = duty cycle. For the sonograms and spectra, see Figures 3 and 4. The maximum possible source level of the FG-SM was not produced during the study.

Sound #	Sound	Sound type	Sound duration (s)	Maximum source level (dB re 1 μPa)
1	500-530 sweep, modulated by 70 Hz, 10 times/s, 50% DC	Sweep square wave	10	180
2	Sweep 500 Hz-20 kHz, duration 1.5 s, repeated 10 times	Sweep sine wave	15	181
3	500-507 sweep, modulated by 499 Hz, 25% DC	Sweep square wave	10	184
4	Sweep 1-4 kHz, 0.5 s, sweep 3-6 kHz, 0.5 s, etc., until 1 sweep 7-20 kHz, 0.5 s	Sweep sine wave	repeat 3 times = 13.5	180
5	500-530/700-730/1,000-1,030/1,200-1,230/1,500-1,530 sweeps, modulated by 70 Hz, 50% DC	Triangle wave	10	188
6	Sweep 5-10 kHz, sweep 0.5 s, sweep 5-15 kHz, 0.5 s, sweep 5-20 kHz, 0.5s	Sweep sine wave	repeat 8 times = 12	181
7	White noise bandwidth: 20 Hz-15 kHz	White noise band	10	174
8	Sweep 5-10 kHz, 0.5 s, sweep 10-15 kHz, 0.5 s, sweep 15-20 kHz, 0.5 s, with increasing amplitude	Sweep sine wave	repeat 8 times = 12	179
9	20 ms, 8 kHz, 280 ms silence × 34	Sine wave	10	164
10	11,000-11,100/13,000-13,100/15,000-15,100/17,000-17,100/19,000-19,100 sweeps, modulated by 70 Hz, 50% DC	FM sine wave	10	178
11	1,000-1,060 sweep, modulated by 70 Hz, 10 times/s, 50% DC	Sweep square wave	10	188
12	17,000-17,100 sweeps, modulated by 70 Hz, 10 times/s, 50% DC	Sweep square wave	10	172
13	7,000 Hz FM, modulated by 2,000 Hz, 1 time/s, 50% DC	Sweep square wave	10	180
14	17,000 Hz FM, modulated by 3,000 Hz, 2 times/s, 50% DC	Sweep square wave	10	176
15	Sweep 7-8 kHz, 0.1 s, sweep 8-9 kHz, 0.1 s, etc., until sweep 9-20 kHz, 0.1 s, with increasing amplitude	Sweep sinus wave	repeat 10 times = 13	177
16	Sweep 1-8 kHz, 1 s, sweep 5-13 kHz, 1 s, sweep 9-20 kHz, 1 s, modulated by 1,000 Hz, 1 time/s, 50% DC	Sweep square wave	repeat 4 times = 12	180

Experimental Procedures

The transducer used to produce the FG-SM's sounds was placed in the pool at the beginning of each working day at least 30 min before the first session started (Figure 1). Each session consisted of a 30-min baseline period (no FG-SM sound emission; only the Beaufort Sea State noise if the session was to include it), followed by a break of around 60 min, after which a 30-min test period (sound emission) started. One session was conducted per day, 7 d/wk, beginning between 0830 and 0900 h.

In each session, the FG-SM's sounds were tested at one of the four SPLs selected in the pilot study and at one of the two background noise levels; each combination was tested six times (48 sessions in all). The SPLs and background noise levels were tested in random order. With the exception of the operator in the research cabin, people were not allowed within 15 m of the pool during tests (i.e., people remained out of sight of the animals) to avoid influencing the seals' behavior. Tests were not carried out during rainfall or

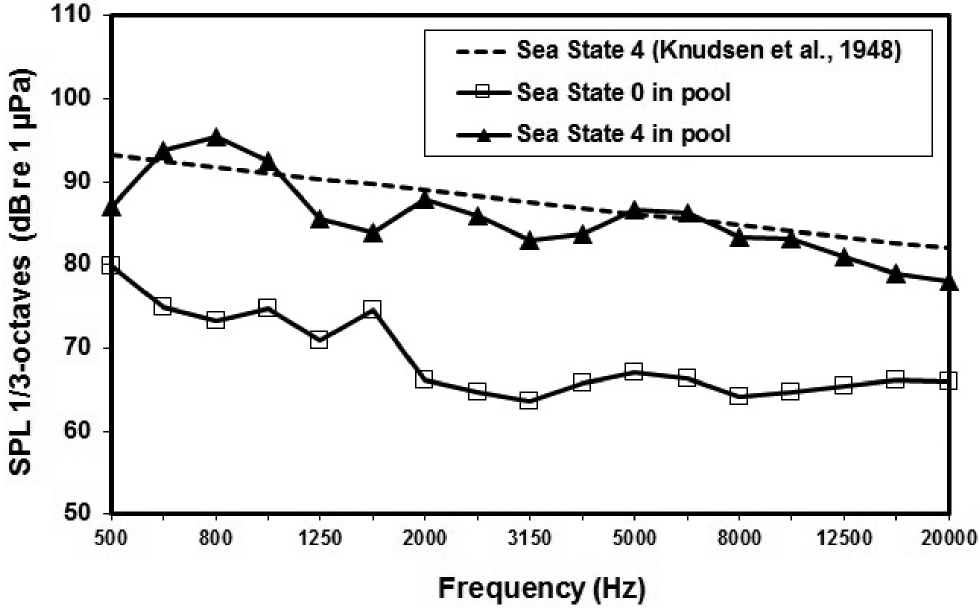

Figure 5. The spectra of the two background noise levels in the pool at which the FG-SM's sounds were tested, with the normal low background noise level resembling the noise level of Beaufort Sea State 0 (SS 0), and the artificially generated level resembling the noise level of SS 4 (⅓ octave bands, SPL averaged over 10 s). Also shown is the theoretical SS 4 level (Knudsen curves with ⅓ octave correction; Knudsen et al., 1948) as measured in the open ocean. SPLs in the North Sea at SS 4 are likely to be higher due to shipping noise.

Table 2. The mean source levels produced by the FG-SM (all 16 sounds) and the mean SPLs in the pool (based on the power sum of all 16 sounds at all 27 measurement points in the pool) that the harbor seals were exposed to during the study. Also shown is the maximum mean (over all 16 sounds) source level of the FG-SM, measured when the seals were out of the pool (this level was not used in the study and was only used to calculate the deterring distance at sea; see "Discussion").

Level description	Source level (dB re 1 µPa)	Mean SPL in the pool (dB re 1 µPa)
Just below behavioral change	134	124
Intermediate	146	136
Intermediate	158	148
Both animals hauled out	170	160
Maximum source level of FG-SM	182	--

when the wind speed was above that which causes SS 4 (5.5 to 7.9 m/s), as under these conditions the FG-SM's sounds may have been partly masked by ambient noise. The study was conducted between February and June 2016.

Behavioral Data Recording, Response Parameters, and Analysis

The spot sampling method was used to record the behavior of the two harbor seals objectively: every 5 s the operator recorded whether each seal's head was under water or in the air; and if it was in the air, the location of the seal was recorded (grid location in the water [in one of the nine rectangles]; Figure 6). Thus, each animal's behavior was scored 360 times per 30-min baseline or test period. So that the seals could be distinguished clearly from each other in the video images, the top of the head of seal 02 was marked with white zinc ointment at the beginning of each day.

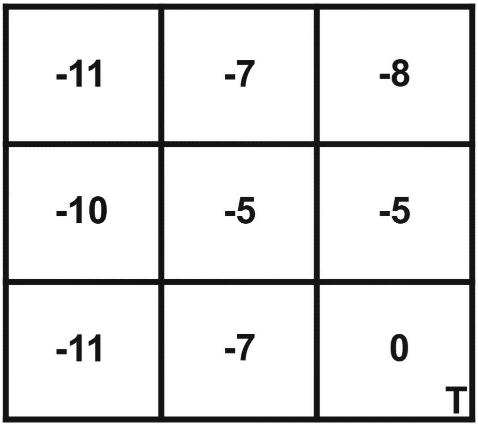

Figure 6. The mean attenuation (in dB) in each of nine grid squares of the 16 sounds in the pool (8 × 7 m); T = location of the transducer (see also Figure 1a).

Four behavioral parameters were used to quantify the harbor seals' responses to the FG-SM's sounds:

1. The distance between their locations and the transducer at scoring moments when the seals' heads were visible during baseline and test periods

2. The number of times the animals jumped during baseline and test periods

3. The percentage of scores for which they were in the water but with their heads above the water surface during baseline and test periods

4. The percentage of scores for which they were hauled out on one of the three platforms (i.e., entirely out of the water) during baseline and test periods

Very few jumps occurred during baseline periods, so, although jumping is considered to be a very strong reaction to sound, numbers of jumps were not submitted to statistical analysis. Initial analysis and graphs showed that the FG-SM's sounds had no effect on the harbor seals' distance from the transducer, and also that the seals did not habituate to the sounds during the study (there was no relationship between session number and recorded behavior).

The remaining two parameters were combined to allow a comparison of the time the harbor seals spent with their heads above the water surface (with either just their heads above the water surface or completely hauled out). Two-tailed paired *t* tests were used where appropriate to compare baselines with associated test periods. Bonferroni corrections for multiple comparisons were applied, resulting in a level of significance of 0.006 (Zar, 1999). In response to sounds at levels that had an effect, seals were predicted to jump more and spend more time with their heads above the water surface or hauled out than during baseline periods.

Results

Baseline Behavior

During baseline periods, both harbor seals usually swam vertical, diagonal ovals in the pool.

Seal 01—On average in baseline periods, seal 01 spent some time with her head above the water surface (19% of scores with SS 0; 20% with SS 4) and very little time hauled out (< 1% of scores with SS 0; 0% with SS 4; Figures 7-9). She only jumped three times in the 48 baseline periods (24 h in total) and only with SS 0. Her average distance (± SD) to the transducer in baseline periods was 5.1 ± 0.8 m with SS 0 and 4.7 ± 1.1 m with SS 4.

Seal 02—On average in baseline periods, seal 02 spent some time with her head above the water surface (19% of scores with SS 0 and 21% with SS 4), and very little time hauled out (0% with SS 0 and in < 1% of scores with SS 4; Figures 8 & 10). She jumped only once in the 24 baseline periods with SS 0 and once in the 24 baseline periods with SS 4. Her average distance (± SD) to the transducer in baseline periods was 5.5 ± 0.4 m with SS0 and 5.4 ± 0.5 m with SS4.

Behavior During Test Periods: Sea State 0

Seal 01—Up to a mean $SPL_{av.rec.}$ of 136 dB re 1 µPa, seal 01 did not respond to the FG-SM's sounds (Figure 7; Table 3). At and above a mean $SPL_{av\ rec.}$ of 148 dB re 1 µPa, she swam more frequently with her head above the water surface in test periods than in the associated baseline periods; but when the mean $SPL_{av.rec.}$ reached 160 dB re 1 µPa, the difference became significant (Figure 7). She also started to haul out (Figure 7) and jumped regularly at $SPL_{av\ rec.}$ of 148 dB (Table 3). Analysis of the combined percentage of scores she spent with her head above the water surface or hauled out (Table 3) showed that at a mean $SPL_{av.rec.}$ of 160 dB, seal 01 reacted significantly to the FG-SM's sounds by removing her head from the water. Her average distance (± SD) from the transducer in all test periods was 5.6 ± 1.0 m.

Seal 02—Up to a mean $SPL_{av.rec.}$ of 160 dB re 1 µPa, seal 02 did not increase the time she spent swimming with her head above the water surface in response to the FG-SM's sounds (Figure 8; Table 3). At and above a mean $SPL_{av.rec.}$ of 136 dB re 1 µPa, she hauled out in test periods slightly, but, until the mean $SPL_{av.rec.}$ reached 160 dB re 1 µPa, not significantly more frequently than in the associated baseline periods (Figure 8). At a mean $SPL_{av.rec.}$ of 160 dB re 1 µPa, she jumped a few times during test periods (Table 3). Analysis of the combined percentage of scores she spent with her head above the water surface or hauled out (Table 3) showed that at a mean $SPL_{av.rec.}$ of 160 dB, seal 02 reacted to the FG-SM's sounds significantly by removing her head from the water. Her average distance (± SD) from the transducer in all test periods was 5.8 ± 0.8 m.

Behavior During Test Periods: Sea State 4

Seal 01—Up to a mean $SPL_{av.rec.}$ of 124 dB re 1 µPa, seal 01 did not respond to the FG-SM's sounds (Figure 9; Table 3). At and above a mean $SPL_{av\ rec.}$ of 136 dB re 1 µPa, she swam slightly, but, until the mean $SPL_{av.rec.}$ reached 160 dB re 1 µPa, not significantly more frequently with her head above the water surface in the test periods than in the associated baseline periods (Figure 9), and she also hauled out a few times (Figure 9) and jumped (starting at $SPL_{av.rec.}$ of 136 dB; Table 3). Analysis of the combined percentage of scores she spent with her head above the water surface or hauled

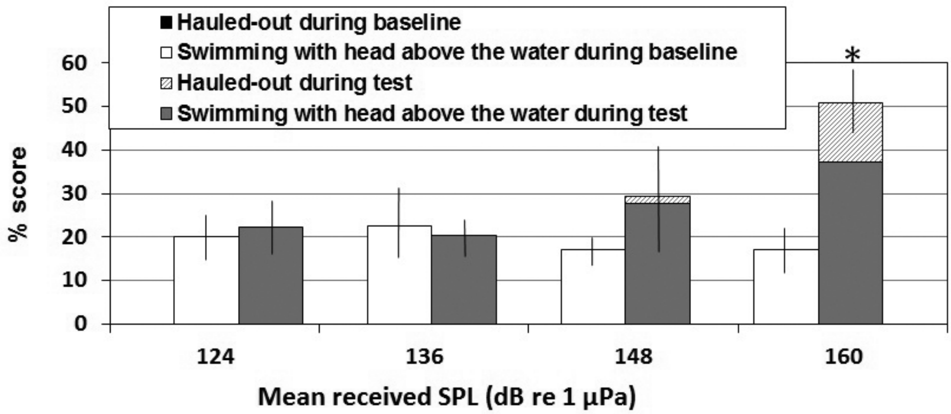

Figure 7. Mean percentage of scores spent swimming with the head above the water surface and hauled out by seal 01 during baseline sessions and test sessions (30-min exposures to the 16 sounds produced by the FG-SM) under noise conditions similar to those of SS 0. *N* = 6 per mean received SPL; error bars show ± SD for the combined scores of both behavioral parameters in test sessions. An asterisk (*) indicates a significant difference between baseline and test periods for the combined scores.

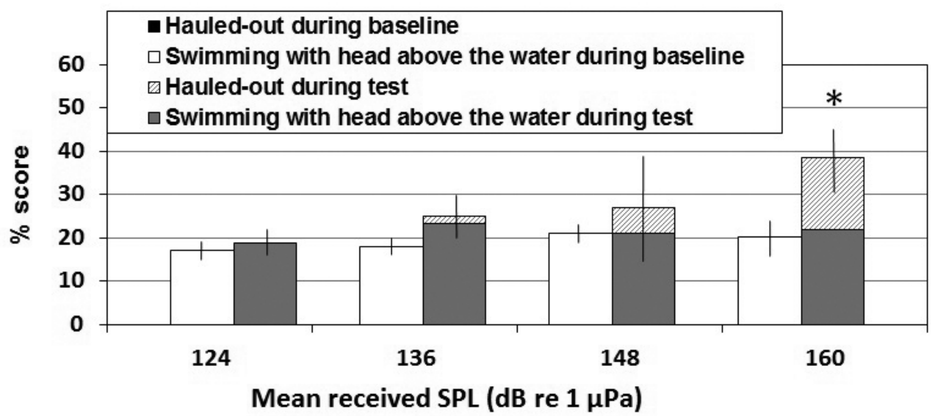

Figure 8. Mean percentage of scores spent swimming with the head above the water surface and spent hauled out by of seal 02 during baseline sessions and during test sessions (30-min exposures to the 16 sounds produced by the FG-SM) under noise conditions similar to those of SS 0. *N* = 6 per mean received SPL; error bars show ± SD over sum of scores of both behavioral parameters. An asterisk (*) indicates significant difference between baseline and test periods (Table 3). Seal 02 did not haul out in the baseline periods.

out (Table 3) showed that at a mean $SPL_{av.rec.}$ of 160 dB, seal 01 reacted to the FG-SM's sounds significantly by removing her head from the water. Her average distance (± SD) from the transducer in all test periods was 5.4 ± 1.1 m.

Seal 02—Up to a mean $SPL_{av.rec.}$ of 148 dB re 1 µPa, seal 02 did not increase the time she spent swimming with her head above the water surface in response to the FG-SM's sounds (Figure 10; Table 3). At and above a mean $SPL_{av.rec.}$ of 136 dB re 1 µPa, she hauled out slightly, but, until the mean $SPL_{av.rec.}$ reached 160 dB re 1 µPa, not significantly more frequently in the test periods than in the associated baseline periods (Figure 10). Only at mean $SPL_{av.rec.}$ of 148 dB re 1 µPa and above did she jump during sessions (Table 3). Analysis of the combined percentage of scores she spent with her head above the water surface or hauled out (Table 3) showed that at a mean $SPL_{av.rec.}$ of 160 dB, seal 02 reacted significantly to the FG-SM's sounds by removing her head from the water. Her average distance (± SD) to the transducer in all test periods was 5.5 ± 0.8 m.

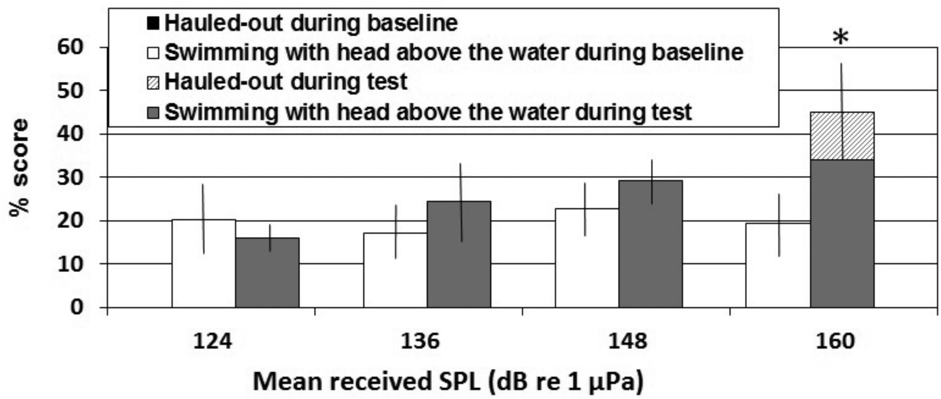

Figure 9. Mean percentage of scores spent swimming with the head above the water surface and spent hauled out by seal 01 during baseline sessions and test sessions (30-min exposures to the 16 sounds produced by the FG-SM) under noise conditions similar to those of SS 4. *N* = 6 per mean received SPL; error bars show ± SD over sum of scores of both behavioral parameters. An asterisk (*) indicates significant difference between baseline and test periods (Table 3). Seal 01 did not haul out in the baseline periods.

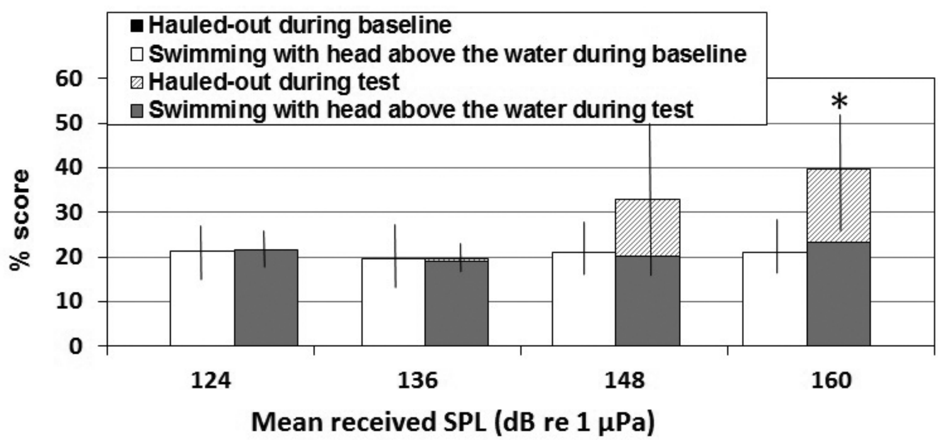

Figure 10. Mean percentage of scores spent swimming with the head above the water surface and spent hauled out by seal 02 during baseline sessions and test sessions (30-min exposures to the 16 sounds produced by the FG-SM) under noise conditions similar to those of SS 4. *N* = 6 per mean received SPL; error bars show ± SD over sum of scores of both behavioral parameters. An asterisk (*) indicates significant difference between baseline and test periods (Table 3). Seal 02 spent very little time hauled out in the baseline periods (< 1% of scores; not visible in the figure).

Table 3. Comparison of harbor seals' behavior in baseline and associated test periods at four $SPLs_{av.rec.}$ (dB re 1 μPa; calculated from all 27 measurement locations in the pool) and two background noise levels (similar to those associated with SS 0 and 4). Comparisons are via paired *t* tests for the combined percentage of scores the seals spent either with their heads above the water surface ("head out") or completely hauled out. Total numbers of jumps in all test periods are shown without statistical analysis. Only five jumps were recorded in all baseline periods (both seals and all levels; 24 h of baseline recording in total per animal). The sample size for each comparison is six sessions (360 scores). Exact *p* values are shown for paired *t* tests when significant ($\alpha = 0.006$ following Bonferroni correction); NS = not significant. In all cases for which the test was significant, the value for the test period was as predicted (i.e., in test periods, the seals spent more time with their heads above the water surface or hauled out than during baseline periods).

		Seal 01		Seal 02	
$SPLs_{av.rec}$ (dB re 1 μPa)	Background noise	Head out/ hauled out	Jumps	Head out/ hauled out	Jumps
124	SS 0	NS	0	NS	0
136	SS 0	NS	0	NS	0
148	SS 0	NS	11	NS	0
160	SS 0	0.001	48	0.001	6
124	SS 4	NS	1	NS	0
136	SS 4	NS	7	NS	0
148	SS 4	NS	23	NS	10
160	SS 4	0.003	42	0.004	13

Discussion

Evaluation

The study was conducted with only two animals. Their hearing was probably representative for harbor seals of their age living in the wild. The hearing sensitivity of the two animals was similar for tonal signals and ⅓-octave noise bands, (Kastelein et al., 2009a, 2009b, 2010), so the differences in their behavior were not due to differences in hearing sensitivity but due to individual differences in the way they responded to sound. The behavioral response data of the present study, though scientifically robust, should be used with caution. Behavior depends not only on hearing sensitivity, but also on many individual properties of animals (e.g., age, sex, experience, genetics, nature or disposition, etc.) and on the context (e.g., season, water depth, distance to shore, being alone or in a group, proximity to a feeding area, etc.). Thus, the behavioral response threshold levels are approximate and will remain approximate even after many more studies, though testing the same sounds on a larger number of individuals would provide a better understanding of the range of received levels that cause the behavioral responses seen in the present study. Variation observed in behavior during the baseline periods was probably due to variations in the environment (e.g., wind, light conditions, and temperature), varying internal conditions (e.g., related to hormonal changes and mood), and chance (i.e., the spot sampling method was used to record behavior).

It is difficult to predict whether wild seals' responses to the FG-SM's sounds at sea would be similar to the responses observed in the captive seals in the present study. However, in a behavioral response study on harbor porpoises (*Phocoena phocoena*), a dose-response relationship was established for pile driving sounds in a pool (Kastelein et al., 2013). The deterring range predicted from that study was similar to ranges observed in the wild (Tougaard et al., 2009; Brandt et al., 2011; Dähne et al., 2013). A behavioral response study on the effect of the FaunaGuard Porpoise Module on harbor porpoises in their natural environment showed that the effective deterrence range was > 1,000 m (Geelhoed et al., 2017).

Individual Variation in Responses

Each of the two harbor seals used a different behavioral strategy to cope with the FG-SM's sounds when they were above a certain SPL. Seal 01 responded by increasing the percentage of time she held her head above the water surface and by jumping more, whereas seal 02 responded by hauling out more frequently and jumping more. However, when, for analysis, the scores for "head out" and "hauled out" were combined, the responses of the seals were similar (Table 3; compare Figures 7 with 8, and 9 with 10). Seals in the wild also show individual variation in responses to sounds such as those from ADDs (Mate et al., 1987). Other playback experiments with marine mammals have also revealed individual differences in response to sounds—for instance, in captive belugas (*Delphinapterus leucas*) subjected to playbacks of offshore oil drilling noise (Thomas et al., 1990) and in harbor seals responding to underwater data communication signals (Kastelein et al., 2006b). It is not clear whether by swimming at the water surface with her head above the water surface, seal 01 was attempting to decrease the received SPL or responding to what she considered a potential threat from below. It is not known how much the received SPL decreases when seals swim at the water surface compared to when they swim below the water surface.

Behavioral Response Threshold SPL

Although significant changes in the time the seals spent with their heads above the water surface ("head out") or completely hauled out occurred when the $SPL_{av.rec.}$ reached 160 dB re 1 µPa, the number of jumps already increased when the $SPL_{av.rec.}$ reached 139 dB re 1 µPa in one animal and 148 dB re 1 µPa in the other animal (Table 3). Because jumps only occurred five times during all baseline periods (24 h in total), jumps were considered to be the most important behavior on which to base the behavioral response threshold $SPL_{av\ rec.}$. Based on numbers of jumps, the behavioral threshold $SPL_{av\ rec.}$ in the present study for both animals, in both ambient noise conditions, appears to be somewhere between 136 and 148 dB re 1µPa. For examples of effective distance estimates of the FG-SM made further on, 142 dB re 1µPa is taken for the calculations.

Research has demonstrated the deterring effects of anthropogenic sounds on harbor seals; however, in most cases, behavioral response threshold values were not derived. Bowles & Andersen (2012) showed that harbor seals touch underwater objects with attached ADDs less frequently than underwater objects without ADDs. Yurk & Trites (2000) reported that ADDs deployed near a bridge over a river reduced the predation of juvenile salmonids by harbor seals. Grey seals (*Halichoerus grypus*) also react to underwater sounds at sea; Fjälling et al. (2006) showed that catch damage is less in salmon-trap nets in the Baltic Sea with ADDs than in nets without them. Anderson & Hawkins (1978) recorded the responses of both captive and wild harbor seals to tones and played-back killer whale (*Orcinus orca*) vocalizations. One sound caused a captive seal to respond, but it habituated quickly to the sound. No responses were seen in wild seals. No source levels or received levels were reported, so the received level may have been below the behavioral response threshold level.

Some behavioral research on harbor seals has provided behavioral response threshold levels. Underwater data transmission signals in the 8 to 18 kHz range produce behavioral response threshold equivalent SPLs (L_{eq} of signal series) of ~107 dB re 1 µPa (Kastelein et al., 2006b) as did 8 kHz tonal signals of 128 dB re 1 µPa, 16 kHz tonal signals of 120 dB re 1 µPa, a 32 kHz signal of 122 dB re 1 µPa, and 45 kHz signals of 128 dB re 1 µPa (Kastelein et al., 2006a). For a frequency modulated signal of around 25 kHz, the behavioral response threshold SPL was between 125 and 137 dB re 1 µPa, so ~131 dB re 1 µPa (Kastelein et al., 2015). Götz & Janik (2010) compared behavioral responses of seals to playbacks of sounds based on a model of sensory unpleasantness for humans, using sounds from ADDs and sounds with assumed neutral properties in different contexts of food motivation. In a captive experiment with food presentation, seals habituated quickly to all sound types presented at normalized received SPLs of 146 dB re 1 µPa (root mean square). Avoidance behavior was observed at received levels of 135 to 144 dB re 1 µPa (sensation levels of 59 to 79 dB).

It is difficult to compare the mean behavioral response threshold level found in the present study with those found in previous studies, as the studies were conducted with sounds that differed in type (noise vs tonal), frequency spectrum (narrow band vs broadband), kurtosis, duty cycle, and sometimes other parameters. It is also not clear whether the animals reacted to instantaneous SPL or the L_{eq} of a sound sequence.

The behavioral response threshold of harbor seals for the sounds of the FG-SM in the present study (many of which were sweeps) is within the range of behavioral response thresholds found for sweeps in previous studies. Behavioral response thresholds for continuous waves tend to be higher than those for sweeps. Whether this is due to differences in frequency (pure tones vs sweeps) or in temporal pattern (continuous vs intermittent sounds), or both, is not clear.

Estimated Effect Ranges at Sea

By combining the results from the present study with information on the source level and frequency range of the signals, and the local background noise and propagation conditions, the extent of the area around the FG-SM in which harbor seal behavior is likely to be influenced can be estimated. To calculate the effect range of the FG-SM at sea for harbor seals, the following information is needed: the mean source level of the FG-SM's sounds (182 dB re 1 μPa), the propagation, the ambient noise level, and the behavioral threshold SPL found in the present study (~142 dB re 1 μPa).

Propagation is difficult to predict as it is dependent on both the signals' frequencies and the local propagation conditions. The frequency range of the FG-SM's sounds is fairly wide (200 Hz to 20 kHz), and it is not known to which of the 16 sounds the harbor seals reacted most, so only a rough estimate can be made. Near the sound source, the sensation level of all 16 sounds made by the FG-SM is similar because their source levels are similar (Table 3), and the audiogram of the harbor seal is rather flat between 250 Hz and 20 kHz (Kastelein et al., 2009a, 2009b, 2010). All 16 sound durations were above the integration time of seal hearing (Kastelein et al., 2010). Using two generic models of attenuation (not including absorption), two rough estimates of the effective range of the FG-SM can be made using the formula

Behavioral threshold SPL = source level - attenuation

142 dB = 182 dB-20log R (in this case, R = 100 m) or

142 dB = 182 dB-15log R (in this case, R = 500 m)

Using the same transducer as used in the present study, Götz & Janik (2015) observed reduced seal numbers up to 250 m from the sound source which produced isolated 200 ms long, 2 to 3 octave-band noise pulses with a peak frequency of 1 kHz at a source level of ~180 dB re 1 μPa. The harbor seals were unaffected at greater distances.

The present study showed that even at a mean received level of 142 dB re 1 μPa, the effect of the FG-SM's sounds was not influenced by ambient noise similar to that experienced during SS 4. At this received SPL, the FG-SM sounds were not masked by the SS 4 noise level. The ambient noise associated with this Sea State was measured in the middle of an ocean (Knudsen et al., 1948); the ambient noise in the North Sea is likely to be higher due to noise from vessel traffic and other activities. However, at some distance from the ship, the frequency of shipping noise is mainly below 1 kHz, whereas most of the FG-SM's sound spectra have energy above this frequency (Figure 4), so they will not be masked to a great extent by vessel noise.

When the FG-SM is used at sea, variation in environmental parameters leads to high levels of variability in the distance at which harbor seals respond to it due to propagation effects (Sertlek & Ainslie, 2014). For this reason, and due to individual and possible temporal differences in response threshold SPLs, distance ranges rather than exact distances at which the FG-SM's sound sequences elicit responses should be considered when assessing effective deterrent ranges.

For the North Sea, the distance from a pile driving site within which PTS could occur in harbor seals has been calculated as between 100 and 200 m (see Table 3 in de Jong & Binnerts, 2013). Thus, in most cases, the FG-SM is likely to be able to deter harbor seals far enough from a pile driving site to prevent PTS, especially in the shallow North Sea (see above).

Recommendations for Users of the FG-SM

As well as its acoustic characteristics, operational characteristics and how and where the FG-SM is used may influence its effect on harbor seals. Harbor seals are unlikely to habituate to, and thus eventually ignore, sounds that occur only rarely. Kastelein et al. (2006a) noted that harbor seals did not habituate to daily 45-min presentations of high-amplitude tone pulses over a period of 40 d. On the other hand, Götz & Janik (2010) showed that captive harbor seals habituated quickly to aversive sounds when food was available during the exposure periods, showing that responses and habituation are context-dependent.

At sea, the FG-SM should not be deployed continuously but only from about 15 min before the start of an activity that is likely to produce loud sounds that may be dangerous to harbor seals. In this way, the animals are encouraged to move away from the activity prior to it becoming potentially harmful, and the sounds of the FG-SM will still remain novel to the animals so that they are less likely to habituate to them.

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