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Brief Behavioral Response Threshold Levels of a Harbor Porpoise (*Phocoena phocoena*) to Five Helicopter Dipping Sonar Signals (1.33 to 1.43 kHz)

Ronald A. Kastelein, Robin Gransier, Marjan van den Hoogen, and Lean Hoek

Sea Mammal Research Company (SEAMARCO), Julianalaan 46, 3843 CC Harderwijk, The Netherlands
E-mail: researchteam@zonnet.nl

Abstract

Helicopter Long Range Active Sonar (HELRAS) is deployed from navy helicopters to detect submarines. Its worldwide use by NATO navies is expected to increase due to the increasing need to detect submarines at greater distances. The 1.33 to 1.43 kHz signals vary in spectrum and duration depending on the circumstances. HELRAS sonar may affect the behavior of harbor porpoises (*Phocoena phocoena*) within a certain range. To investigate this, a harbor porpoise in a large pool was exposed to five HELRAS signals with different spectra, each of 1.25 s duration, at multiple sound pressure levels (SPLs), which had been determined in a pretest. During each transmission, the presence or absence of a brief behavioral response (defined as a sudden change in swimming speed or swimming direction during sound emission) by the harbor porpoise was recorded. A 50% response rate was observed at mean received SPLs (averaged over all measurement points in the pool) of between 124 and 140 dB re 1 µPa, depending on the signal. A single emission caused no response at received SPLs below around 102 dB re 1 µPa (sound exposure level: 103 dB re 1 µPa^{2}s). The highest level needed to induce a brief response in the harbor porpoise occurred when it was exposed to a down-sweep without harmonics. Therefore, of the five tested signals, this signal will presumably have the least effect on harbor porpoises, and its use could help to minimize the potential effects of HELRAS sounds during peace time exercises.

Key Words: acoustics, anthropogenic sounds, behavior, navy, odontocete, harbor porpoise, *Phocoena phocoena*

Introduction

Knowledge of the hearing systems and behavior of many marine animals is limited, but sound is particularly important for them. Sound can be used as a means of orientation, communication, and to locate prey, conspecifics, and predators (Richardson et al., 1995). Therefore, marine animals are likely to be affected by noise in their environment; noise in the oceans may have negative physiological, auditory, and/or behavioral effects (National Research Council [NRC], 2003).

Background noise in the oceans consists of natural and anthropogenic noise. Anthropogenic noise has increased steadily during the last century (McDonald et al., 2006, 2008). Navies worldwide contribute to the ambient noise by employing shipping, explosions during exercises and removal of ammunition, and sonar systems. Navies use various types of sonar systems, each with different goals and detection abilities. At present, NATO navies are all using, or considering using, a helicopter dipping sonar system—the Helicopter Long Range Active Sonar (HELRAS) system—to detect submarines (Watts, 2005). This system produces signals between 1.33 and 1.43 kHz with various signal durations. HELRAS signals are high intensity sounds (source level: 218 dB re 1 µPa at 1 m rms; L-3 Oceans Group, 2007), and it is unclear how marine mammals respond to them.

The response of the harbor porpoise (*Phocoena phocoena*) to HELRAS signals is of particular interest because this odontocete species has a wide distribution area in coastal waters of the Northern Hemisphere and has functional hearing over a very wide frequency range (250 Hz to 160 kHz; Kastelein et al., 2010). Harbor porpoises are known to be relatively easily deterred by certain 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., 1995, 1997, 2000, 2001, 2006; Laake et al., 1998; Culik et al., 2001; Johnston, 2002; Olesiuk et al., 2002; Teilmann et al., 2006), offshore wind turbines (Koschinski et al., 2003), underwater data communication systems (Kastelein et al., 2005a), airgun sounds (Lucke et al., 2009), and 1 to 2 kHz and 6 to 7 kHz naval sonar sweeps (Kastelein et al., 2011a).

Avoidance threshold levels of harbor porpoises have been determined for noise bands around 12 kHz, a continuous 50 kHz tone, and continuous and pulsed 70 and 120 kHz tones (Kastelein et al., 2005a, 2008a, 2008b). These studies show that stimulus properties such as the bandwidth, spectrum, duration, temporal pattern, rise time, and the received sound pressure level (SPL) play an important role in the effect a sound may have on the behavior of harbor porpoises.

The brief behavioral responses (sudden changes in swimming speed or swimming direction) of a harbor porpoise to HELRAS signals were recorded in the present study. The goal was to compare the 50% brief behavioral response rate for single pulses of five different HELRAS signals, each presented at six mean received levels.

Methods

Study Animal

A 5-y-old male harbor porpoise (identified as No. 02) was used in this study. During the study, his body weight was around 36 kg, his body length was 145 cm, and his girth at axilla around 76 cm. The hearing of this harbor porpoise was assumed to be representative of animals of his age and species as it was measured shortly before the present study and was similar to that of other young adult harbor porpoises (Kastelein et al., 2002, 2009, 2010).

Study Area

The study was conducted at the SEAMARCO Research Institute, the Netherlands, in a remote and quiet location specifically selected for acoustic research. The animal was kept alone in a pool complex designed and built for acoustic research, which consisted of an outdoor pool (12 × 8 m, 2 m deep) connected via a channel (4 × 3 m, 1.4 m deep) with an indoor pool (8 × 7 m, 2 m deep; Figure 1). 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 fiber 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 fiber 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 sea water 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 to be as quiet as possible. This was done by choosing low noise pumps, mounting the pumps on rubber mats, and connecting the pumps to the circulation pipes with very flexible hoses. The water temperature

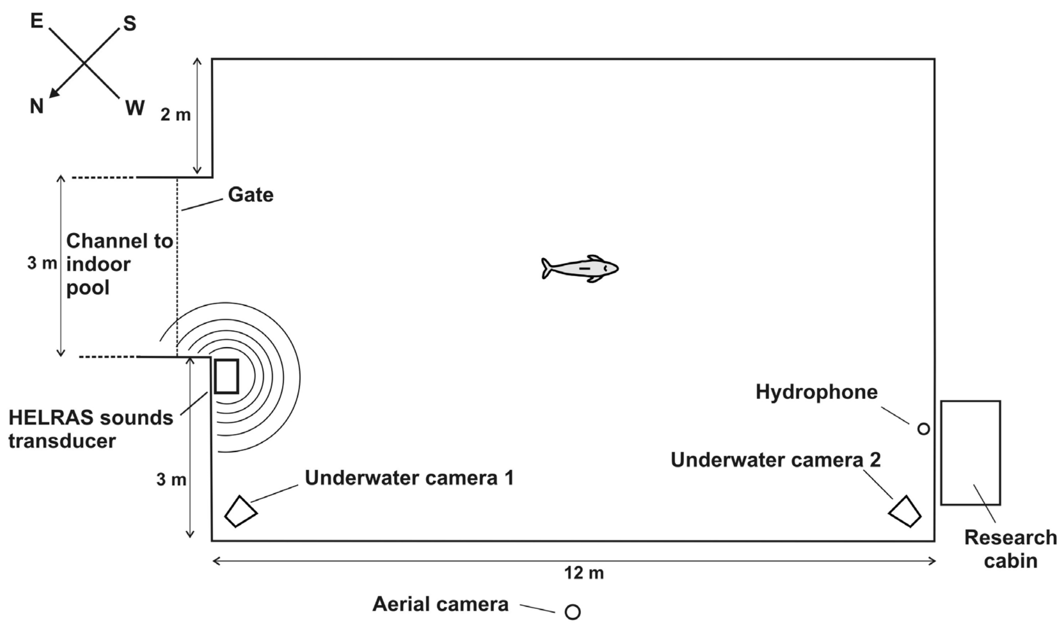

Figure 1. Top scale view of the study facility, showing the study animal, the location of the aerial camera, the two underwater cameras, the underwater transducer emitting the HELRAS signals, and the listening hydrophone. Also shown is the research cabin that housed the equipment and the operator.

during the study period varied between 9 and 12° C, and the salinity was around 34‰. There was no current in the pool during the experiments as the water circulation pump and air pump of the adjacent biofilter were shut off 30 min before the test sessions were started. 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 adjacent to the pool (Figure 1).

Test Stimuli

The harbor porpoise's brief responses to five HELRAS signals were tested. The signals (Table 1) were manipulated and synthesized versions of three signals provided as representative by the manufacturer of HELRAS (L-3 Communications, Ocean Systems Division, Sylmar, CA, USA). HELRAS signals are either continuous wave (CW) signals with durations of 0.3 to 10 s at nominal frequencies of 1,311, 1,380, and 1,449 Hz, with various amplitude envelopes, or frequency-modulated (FM) signals with durations of 0.16 to 5 s and bandwidths from 50 to 300 Hz. Three representative signals were manipulated to make them of consistent duration (1.25 s, which falls within the range used for HELRAS and is likely to be used in shallow coastal waters). Two further signals were synthesized, which were similar to the original recordings but without the harmonics, in order to allow an estimation of the effect of harmonics on the harbor porpoise's brief responses. Spectra (⅓-octaves) of the five HELRAS signals are shown in Figure 2. The spectra of the two signals without harmonics were very similar and the spectra

Table 1. The characteristics of the five HELRAS signals used to determine the 50% brief response SPLs of a harbor porpoise; levels of the harmonics are relative to the level of the fundamental frequency.

HELRAS signal	Description	Relative level of 3rd harmonic	Relative level of 5th harmonic
CW	1,380 Hz continuous wave (CW)	No harmonic	No harmonic
CWh	1,380 Hz CW with harmonic distortion	-18 dB	< -30 dB
CWht	1,380 Hz CW with cosine tapers at start and end and harmonic distortion	-18 dB	< -30 dB
DS	1,330 Hz to 1,430 Hz down-sweep (DS)	No harmonic	No harmonic
DSh	1,330 Hz to 1,430 Hz DS with harmonic distortion	-14 dB	< -30 dB

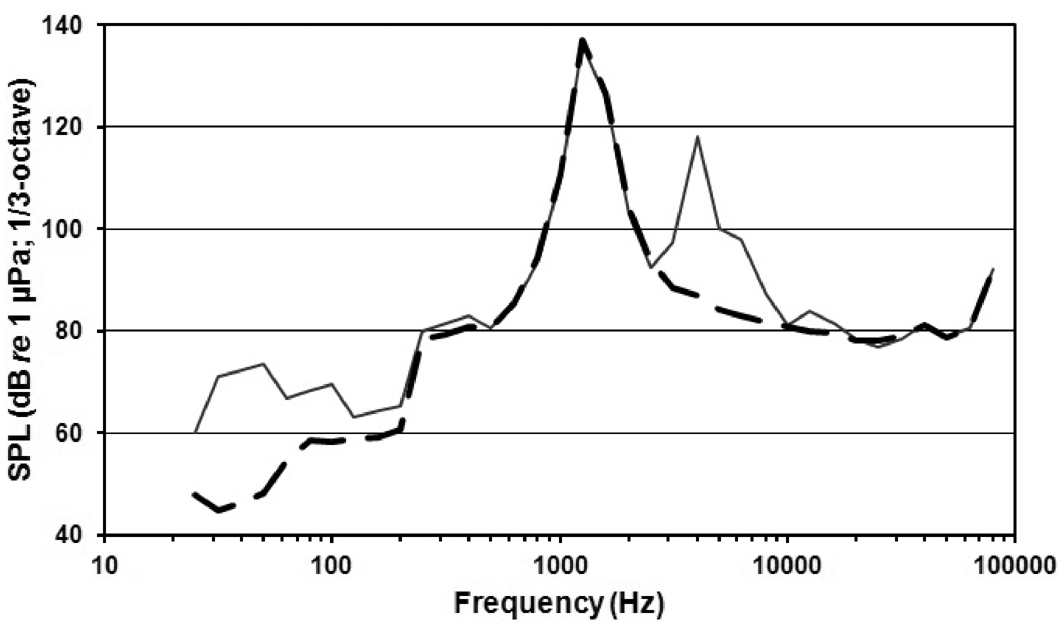

Figure 2. Spectra (⅓-octaves) of the continuous wave (CW) signal (dashed line; the spectrum of the down-sweep [DS] signal was identical) and of the CWh signal (solid line, the spectra of CWht and DSh signals were similar) as recorded in the pool.

of the three signals with harmonics were also very similar. The signals with harmonic distortion exhibited third and fifth harmonics, 14 to 30 dB below the level of the fundamental frequency. The waveforms, as recorded in the pool, were shown by Kastelein et al. (2011b).

The HELRAS signals were created as WAV files. All signal processing was done with *Cool Edit Pro*. The CW signal was a synthesized 1,380 Hz CW pulse with a duration of 1.25 s, with 50 ms cosine tapers at start and end. The CWh signal was made from the middle section of a recording of a 1,380 Hz CW with an extended cosine amplitude taper, harmonic distortion, and a duration of 5 s, with 50 ms cosine tapers at start and end. The CWht signal was made from an original HELRAS signal recording of a 1,380 Hz CW with a cosine squared amplitude taper, harmonic distortion, and a duration of 10 s, by compressing the duration to 1.25 s while keeping the signal frequencies constant. The down-sweep (DS) signal was a synthesized 1,130 to 1,430 Hz FM sweep with a duration of 1.25 s, with 50 ms cosine tapers at start and end. The DSh signal was made from a recording of a 1,130 to 1,430 Hz FM DS with a duration of 5 s by compressing the duration to 1.25 s while keeping the signal frequencies constant (Table 1).

The HELRAS system is very flexible: frequencies, pulse durations, bandwidths, amplitude profiles (i.e., the portion of pulses forming tapers at start and end of a signal), and amplitudes are selected by the operator during use, depending on the circumstances. The signals used in the present study are representative, but they are only a small selection of all possible signals than can be created with the HELRAS system.

To prevent the production of unwanted on-offset transients, a 1 s silence was programmed before and after each signal in Adobe *Audition*, Version 3.0. A schematic diagram of the equipment used to configure and emit outgoing signals and record video and underwater sounds is shown in Figure 3. The digitized HELRAS signals (sample frequency 48 kHz) were played back by a laptop computer (Medion - MD96780) via a pre-amplifier (10×) to an audio power amplifier (E&W-HS-1800), the output of which was controlled digitally with a custom-built attenuator (SEAMARCO - AS 2009-02). After going through an isolation transformer, the signals were projected under water via a balanced tonpilz piezoelectric

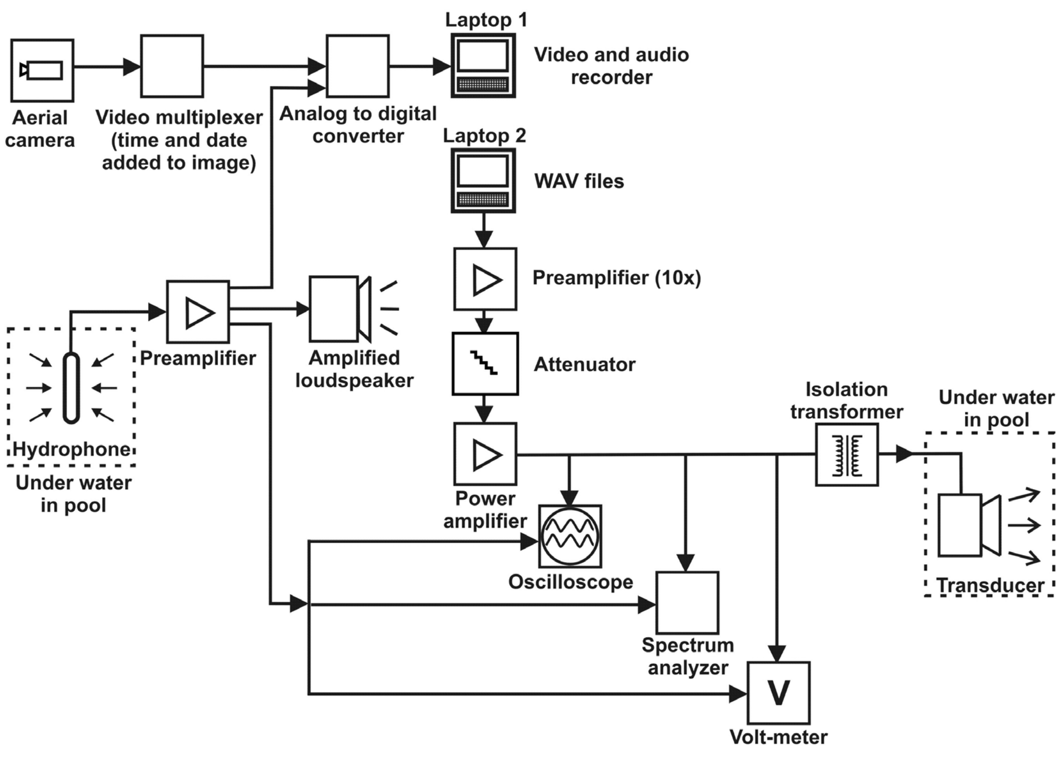

Figure 3. Block diagram of the signal generation and control systems, and the listening and recording equipment used in the harbor porpoise behavioral response study.

acoustic transducer (Lubell - LL1424HP) suspended 2 m below the water surface at the northeastern end of the pool (Figure 1). The output of the sound system to the transducer was monitored with an oscilloscope (Tektronix - 2201), a voltmeter (Agilent - 34401A), and a spectrum analyzer (Velleman - PCSU1000).

Video and Audio Recording

The animal's behavior was filmed from above by a camera (Conrad-750940) with a wide-angle lens and a polarizing filter to prevent saturation of the video image by glare from the water surface. The camera was placed 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 that 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 a laptop computer (Medion - MD96780). The animal was also filmed underwater by two underwater video cameras (Ocean Systems Inc. - Delta Vision B/W), which were placed in two corners of the pool (Figure 1). The images were made visible to the operator on two monitors in the research cabin.

For behavioral response analysis, the audio part of the background noise and the played back HELRAS signals were recorded via a hydrophone (Labforce - 90.02.01) and a custom-built pre-amplifier (SEAMARCO - CCAMS1000-2). The output of the pre-amplifier was digitized via the analog-to-digital converter and recorded on the computer in synchrony with the video images. The output was also fed to an amplified loudspeaker so that the operator in the research cabin could monitor the background noise and the test signals during sessions.

Determination of the Source Level Used in the Tests

During a 2-wk pretest period, all five HELRAS signals were played back with gradually increasing SPLs until the harbor porpoise showed a brief response (defined as a sudden change in swimming speed or swimming direction). The SPL at which a response occurred varied per HELRAS signal.

In the actual tests, each HELRAS signal was tested at six source levels (6 dB intervals), which were estimated from the pretests to cause brief responses in between 10 and 90% of cases. The DS signal could only be transmitted at five levels (6 dB intervals) before the highest possible output level of the power amplifier (E&W - HS1800) was reached.

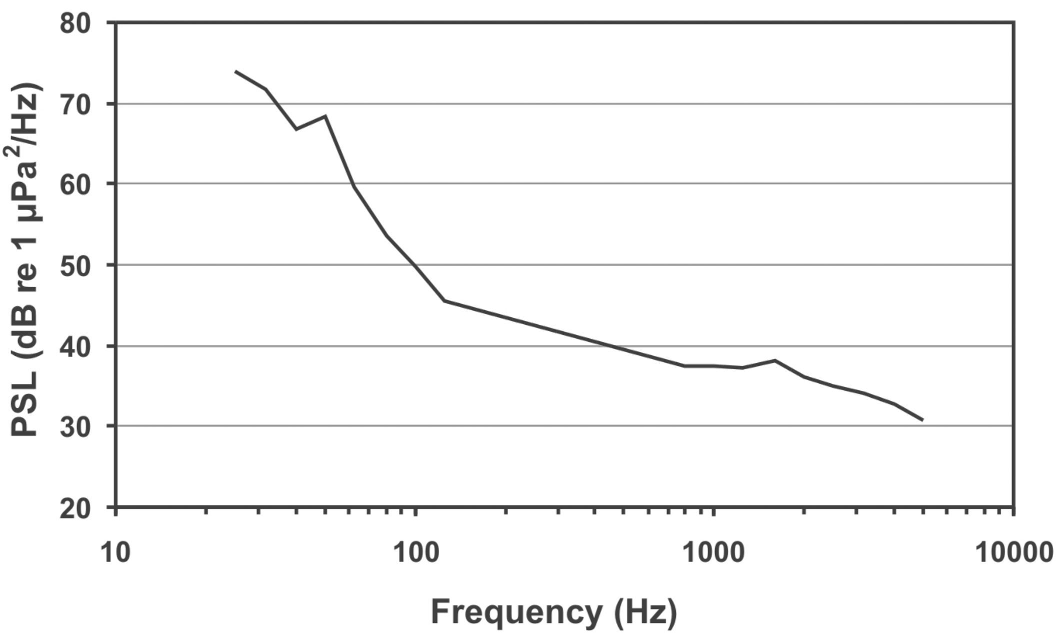

Figure 4. The mean ($n = 3$) background noise level in the pool between 25 Hz and 5 kHz, measured at depths of 0.5 m, 1 m, and 1.5 m; results are given as pressure spectrum levels (PSL) calculated from the SPL measurement in ⅓-octave bands. The background noise level was so low that at frequencies above 3.15 kHz, the background noise level was dominated by the instrumentation noise levels.

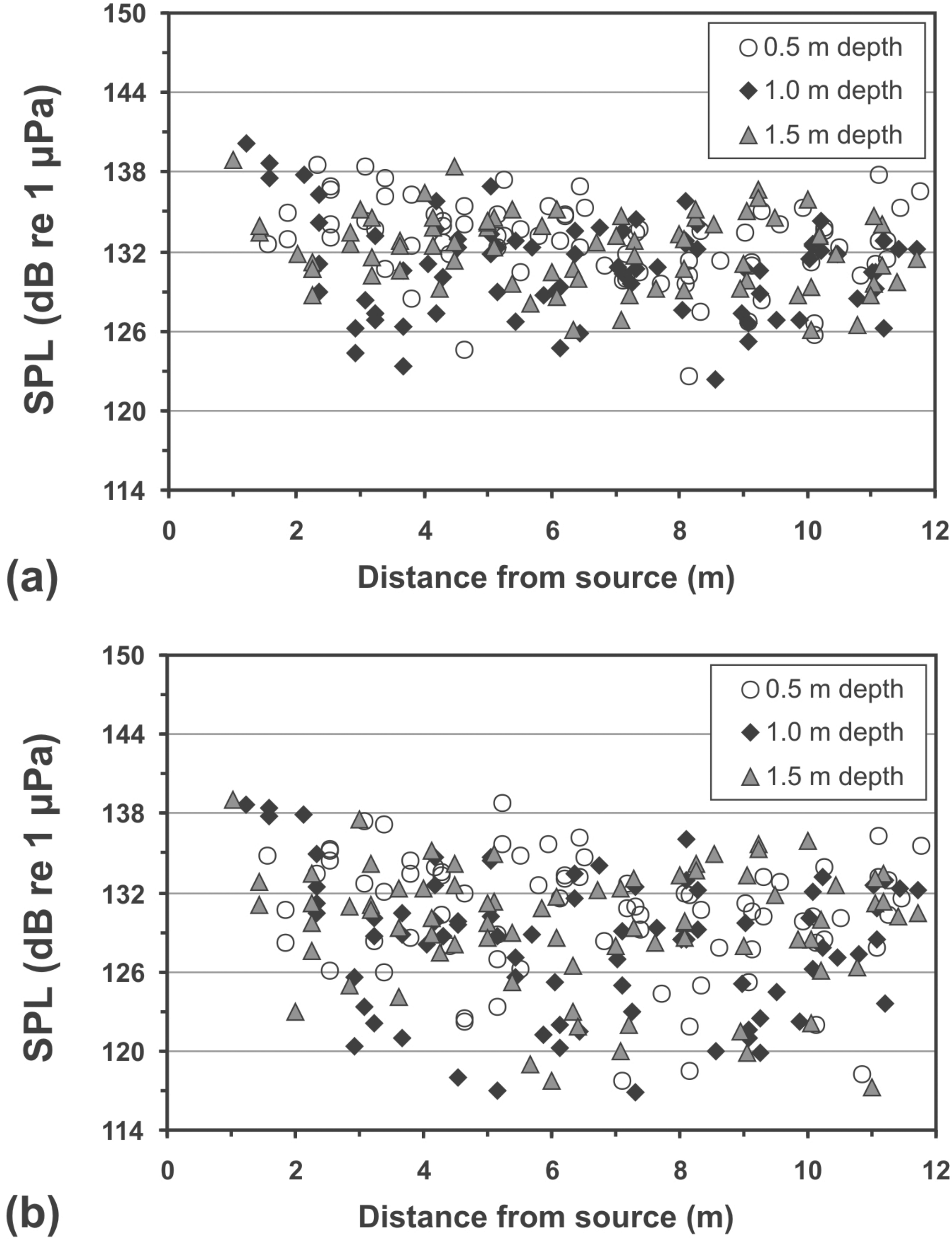

Figure 5. The SPL distribution of the DS (a) and CWht (b) signals in the study pool; the SPL distribution of the CW signal was similar to that of the DS; and those of the CWh and DSh were similar to that of the CWht. The transducer emitting the HELRAS signals was at a depth of 2 m.

Acoustic Measurements
The recording and analysis equipment consisted of two Bruel & Kjaer (B&K) 8106 hydrophones and one B&K 8101 hydrophone with custom-built power supply; a B&K PULSE 3560 D multichannel high-frequency analyzer; and a laptop computer with B&K PULSE software *Labshop*, Version 12.1. The system was calibrated with a B&K 4223 pistonphone. The sample rate was 262,144 Hz.

Background Noise and Sound Measurement Equipment
The background noise in the pool between 25 Hz and 160 kHz was measured. The mean pressure spectrum level of the background noise is shown in Figure 4.

SPL Distribution of HELRAS Signals
In dedicated measurement sessions, while the animal was kept in an adjacent pool, the sound distribution in the pool was measured for the different test stimuli. The SPLs (dB re 1 μPa) were averaged over the duration of the signals. The duration (t_{90} in s) was determined as the time interval between the points at which the cumulative sound exposure (the integrated broadband sound pressure squared) reached 5 and 95% of the total exposure (i.e., when the duration contained 90% of the total energy in the signal; Madsen, 2005).

To determine the sound distribution and the mean received SPL in the pool, the SPL for each of the five HELRAS signals was measured once at 77 locations (on a horizontal grid of 1 m × 1 m). The SPL was measured at three depths per location on the grid (0.5, 1.0, and 1.5 m below the water surface). Thus, 231 measurements were made for each of the five HELRAS signals (Figure 5). At a source level of ~139 dB re 1 μPa (for each signal), the mean SPL in the pool was 130 dB (SD ± 6 dB) for the CW, 130 dB (SD ± 5 dB) for the CWh, 129 dB (SD ± 5 dB) for the CWht, 132 dB (SD ± 3 dB) for the DS, and 131 dB (SD ± 3 dB) for the DSh signal.

Experimental Procedure
Ten minutes before each session started, the gate to the pool was closed (Figure 1). Each session consisted of a 60- to 90-min test period containing 20 to 30 sound emissions (one every 3 min, resulting in a duty cycle of 0.7%). In each session, all five HELRAS signals were tested. For each emission, one HELRAS signal-source level combination was selected randomly from all 29 combinations. Sessions were continued until 24 emissions per HELRAS signal-source level combination had been conducted, which resulted in a total of 696 emissions over 30 sessions.

One session was conducted per day, normally 5 d/wk, beginning between 1000 and 1600 h. A programmable interval timer was used to tell the operator (via a light) when to switch on the WAV file producing a HELRAS signal. During the tests, personnel were not allowed within 10 m of the pool. To ensure low ambient noise, tests were not carried out during rainfall or when the wind speed was sufficient to increase the general background noise level (this generally occurred above Beaufort 4). The study was conducted in September and October 2010.

Analysis
A brief response was defined as a sudden change in swimming speed or swimming direction during the signal emission. For consistency, all the recorded video images were analyzed afterwards by one person who could not hear the signal but focused on images made at the time a signal could be produced. The person was not aware of the SPL of the trials. The outcome was simple: a brief response either occurred or did not occur. In all cases, the behavior was very clear-cut and easy to categorize. No brief responses occurred outside the signal presentations due to the very controlled and quiet environment.

The SPL distribution in the pool was fairly homogenous, and the animal normally used the entire pool. The onset of sound transmission was determined by a time schedule and not by the location of the animal, so differences in received SPL caused by differences in his location in the pool were considered to be equally distributed over all signal presentations (and, thus, over all HELRAS signals and levels). Therefore, the mean SPL of all 231 measurements was taken as the mean received SPL (the sound level experienced by the harbor porpoise) for each source level setting. The percentage of emissions resulting in a brief response was plotted for each HELRAS signal type against the mean received SPL. From the resulting psychometric functions, the mean received SPL of each HELRAS signal type that caused a brief response in the harbor porpoise in 50% of the signal presentations was determined.

Results

When no sounds were emitted, the harbor porpoise usually swam large clock-wise ovals in the pool and made regular long dives alternated with shorter dives. All the observed brief responses occurred during the 1.25-s transmissions of the HELRAS signals and consisted of approximately one strong tail movement bringing about a sudden change in swimming speed and direction after which the animal's behavior returned to normal. The animal did not avoid the area near the underwater transducer during sessions or at any other time. The psychometric functions show that the brief response rate increased as the mean received SPL of the five HELRAS signals increased (Figure 6). The 50% brief response threshold levels derived from these psychometric functions (Table 2) were different for the five different HELRAS signals. Of the HELRAS signals, CWh and CWht created brief responses in 50% of the exposures at relatively low received SPLs, CW and DSh created brief responses at intermediate received SPLs, and DS created brief responses at relatively high received SPLs. At the signal presentation rate of the present study (one signal/3 min, 20 to 30 signals/d), no habituation was observed during sessions or over the course of the 2-mo study.

Discussion

Evaluation

This study was conducted with only one animal, but his hearing was very similar to that of two other male harbor porpoises of the same age (Kastelein et al., 2002, 2009, 2010) and was therefore probably representative of the hearing of harbor porpoises of his age. The study should be repeated with other harbor porpoises as responses can vary between individual porpoises (Kastelein et al., 2000, 2001, 2008b), but this is unlikely to be possible in the near future. Worldwide, only a few harbor porpoises are kept in captivity, and the facilities that keep this species are not designed (i.e., quiet enough) for acoustic behavioral response studies.

Having the harbor porpoise swim freely in the pool was preferred over a trained methodology because free swimming is more comparable to the situation in the wild. The 24 sound transmissions per signal-source level combination were enough to even out small inter-trial differences in received levels for each of the six levels per HELRAS signal (five levels for the DS signal). The mean SPL in the pool was used to approximate the mean SPL received by the harbor porpoise because he could move several meters within the 1.25-s signal duration, and the wave interference differences (locations of the nodes and anti-nodes, and hence the locations of minimum and maximum resonance) in the pool changed rapidly during that period with the changing frequency; both had averaging effects on the received signal. However, harbor porpoise hearing is directional (Kastelein et al., 2005b), so the orientation of the harbor porpoise must have influenced the actual perceived level. To some degree, the directionality of hearing was counterbalanced by the reverberations in the pool and the movement of the animal. In addition, the directionality of hearing decreases with decreasing frequency so the perceived SPL of the 1.33 to 1.43 kHz HELRAS signals was probably close to the received SPL. Overall, the use of the mean SPL seems therefore justified. The maximum SPLs used were so low that they were not a deterrent as the animal did not change his general swimming pattern in the pool for

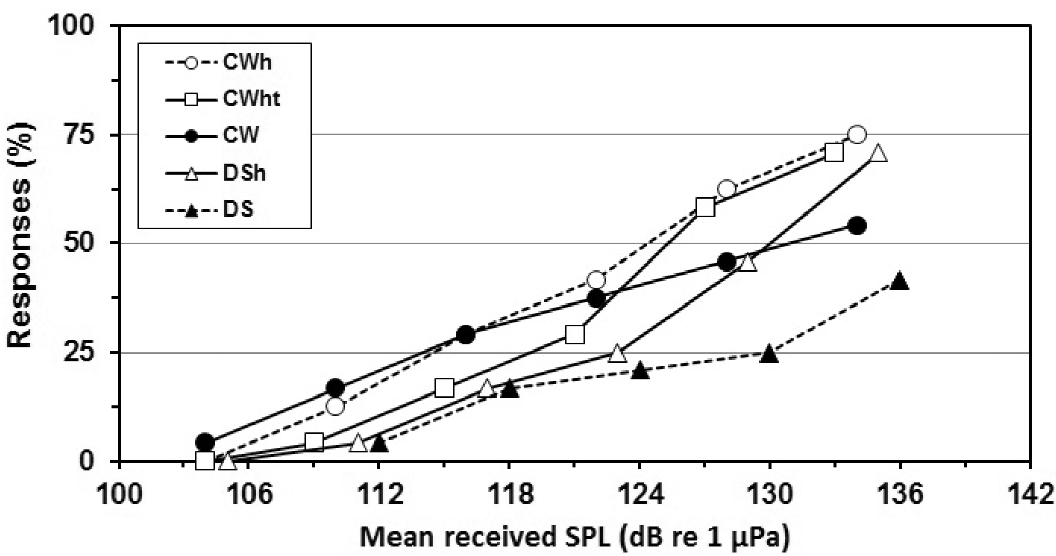

Figure 6. The mean received SPL vs the brief response rate (percentage of 24 sound emissions in which a brief behavioral response, consisting of a strong tail movement followed by a change in swimming speed and/or direction, occurred) for the five HELRAS signals; for sound exposure levels (dB re 1 µPa^{2}s), add 1 dB to the SPL values.

Table 2. The mean received SPLs (for sound exposure levels [dB re 1 µPa²s], add 1 dB to the SPL values) of the HELRAS signals that caused a brief response in the harbor porpoise in 50% of the transmissions (present study), the 50% detection threshold levels of the same harbor porpoise for the same HELRAS signals (Kastelein et al., 2011b), and the difference in dB between the mean received SPLs causing a brief response in 50% of emissions and the 50% detection threshold levels; also shown are the same animal's 50% brief response mean received SPLs for two sweep types in a similar frequency range as the HELRAS signals (1 to 2 kHz signals with and without harmonics; described as "startle responses" by Kastelein et al., 2012), and the 50% detection threshold levels for those sweeps (Kastelein et al., 2011b).

Signal	Mean received SPL causing brief responses in 50% of the emissions (dB re 1µPa)	50% detection threshold SPL (dB re 1µPa)	50% brief response received SPL -50% detection threshold (dB)
HELRAS CWh	124	76	48
HELRAS CWht	125	74	51
HELRAS CW	131	75	56
HELRAS DSh	130	76	54
HELRAS DS	144*	77	67
1-2 kHz without harm	133	75	57
1-2 kHz with harm	99	58	41

* Extrapolated with the following formula: mean received SPL = (50 + 150.56)/1.3889. This extrapolation was needed because at the maximum mean received SPL level that could be produced without distortion of the signals (136 dB re 1 µPa), the animal only responded in 42% of the signal emissions.

more than a second during the signal presentation and did not avoid the area near the transducer.

Signal rise time is one determinant of whether an acoustic signal causes a brief response in a mammal or not (Götz & Janik, 2011). Alongside many other parameters, the amplitude profile (the portion of the pulse forming tapers at start and end, i.e., the rise and fall time) is selected by HELRAS system operators depending on the circumstances. In particular, shorter rise and fall times change the characteristics of the emitted spectrum (producing signals with a broader bandwidth) and may increase the likelihood of harbor porpoises exhibiting a brief response.

The brief response SPLs derived from this research represent the lowest end of the spectrum of behavioral responses to a sound (in the context of the present study). Higher sound levels may deter the animals from optimal foraging areas or change their behavior for a longer period of time to ecologically less optimal behavior. The reaction of harbor porpoises to the HELRAS sounds is very likely to be context-dependent. The context in the pool was kept as constant as possible in order to compare the effect of the five HELRAS sounds. In the wild, the context varies greatly (for instance, depending on season, location, weather, during which activity the sound is received, social setting, physiological state of the animals, etc.), and, thus, the harbor porpoise's reaction varies. The goal of the present study was to compare the effects of the five HELRAS signals on the behavior of a harbor porpoise. The data indicate that different signals in the same frequency range, at the same received level, may cause the same degree, or different degrees, of behavioral responses in harbor porpoises.

Comparison with 50% Brief Response Rates for Other Signals

The 50% brief response SPLs found for the signals used in the present study may be compared with the same harbor porpoise's 50% brief response SPLs for two other sweep types (described as "startle responses" by Kastelein et al., 2012), with 50% detection thresholds for the signals used in the present study (Kastelein et al., 2011b) and with detection thresholds for the other sweep types (Kastelein et al., 2011a; Table 2). As reported by Kastelein et al. (2011a), the frequency content of signals plays an important role in their detection by harbor porpoises, and in the occurrence of brief responses, due to harbor porpoises' highly sensitive hearing for high-frequency signals. Brief responses to 1 to 2 kHz sweep signals without harmonics (Kastelein et al., 2012) occur at similar broadband SPLs as brief responses to HELRAS signals in the present study. The same effect is seen for the detection threshold (Kastelein et al., 2011b). It can be concluded that the brief response is mainly elicited by the fundamental frequencies of the HELRAS signals used in the present study, and not by their relatively weak high-frequency components. Signals containing strong high-frequency components elicit brief responses at lower broadband SPLs than signals without strong high-frequency components (Kastelein et al., 2012). Therefore, when predicting brief responses from detection thresholds by means of a broadband SPL, the broadband SPL level must be related to the entire frequency spectrum of the signal and to the harbor porpoise's full spectrum of hearing.

Relevance to HELRAS Use

The brief response occurs somewhere on the gradient of received SPLs to which animals are exposed. In the context of the present study, single emissions (one every 3 min) of HELRAS signals caused effectively no brief responses at SPLs below around 102 dB re 1 μPa (Figure 6). The brief response is similar to a startle response, which prepares for fight or flight behavior in animals that are facing external threats and is an index of the preparatory state of the animal (Fox et al., 2006). Whether or not a harbor porpoise that is startled by a sound actually flees the area depends on the level of arousal in the animal and on whether the sound is perceived as a threat. It also depends on other factors such as the energetic cost and benefit of staying in or leaving the area.

In normal naval operation, the duty cycle of the HELRAS system varies between 5 and 10%. Assuming signals similar to those used in the present study are in use, the radius around the dipping sonar system, beyond which it probably elicits no behavioral response in harbor porpoises, can be calculated from the results of the study, the source level of the sonar system, and information on the background noise and propagation conditions. The approximate zone of influence of the HELRAS can be calculated by using a typical HELRAS source level, a transmission loss (TL) calculated with a simple spreading law, and appropriate attenuation for harbor porpoise habitat. For example, assuming a source level of 218 dB re 1 μPa and spherical spreading with attenuation ($\alpha = 0.06$ dB/km) ($TL = 20\log[R] + \alpha R$), levels would not fall to the 102 dB response threshold level until the range (R; distance from the source) was in the order of 100 km. In some cases, the zone of influence will be limited more by ambient noise levels than by distance.

The mean received SPLs of the CWh and CWht signals that caused a brief response in 50% of the cases were 5 dB lower than those of the CW and DSh signals and about 20 dB lower than those of the DS signal. Therefore, at the same source level, the use of the DS signal will have the least effect on harbor porpoises, and the use of the other four signals will have a greater effect.

Acknowledgments

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Literature Cited

Amundin, M., & Amundin, B. (1973). On the behaviour and study of the harbour porpoise (*Phocoena phocoena*) in the wild. In G. Pilleri (Ed.), *Investigations on cetacea* (Vol. 5, pp. 317-328). Bern, Switzerland: Institute for Brain Research.

Culik, B. M., Koschinski, S., Treganza, N., & Ellis, G. M. (2001). Reactions of harbour porpoises *Phocoena phocoena* and herring *Clupea harengus* to acoustic alarms. *Marine Ecological Progress Series*, *211*, 255-260. http://dx.doi.org/10.3354/meps211255

Fox, N. A., Ashley Hane, A., & Pérez-Edgar, K. (2006). Psychophysiological methods for the study of developmental psychopathology. In D. Cicchetti & D. J. Cohen (Eds.), *Developmental psychopathology* (Vol. 1, pp. 381-426). Hoboken, NJ: Wiley & Sons.

Götz, T., & Janik, V. M. (2011). Repeated elicitation of the acoustic startle reflex leads to sensitisation in subsequent avoidance behaviour and induces fear conditioning. *BMC Neuroscience*, *12*(30). http://dx.doi.org/10.1186/1471-2202-12-30

Johnston, D. W. (2002). The effect of acoustic harassment devices on harbour porpoises (*Phocoena phocoena*) in the Bay of Fundy, Canada. *Biological Conservation*, *108*, 113-118. http://dx.doi.org/10.1016/S0006-3207(02)00099-X

Kastelein, R. A., Hoek, L., & de Jong, C. A. F. (2011a). Hearing thresholds of a harbor porpoise (*Phocoena phocoena*) for sweeps (1-2 kHz and 6-7 kHz bands) mimicking naval sonar signals. *The Journal of the Acoustical Society of America*, *129*, 3393-3399. http://dx.doi.org/10.1121/1.3559679; http://dx.doi.org/10.1121/1.3569739

Kastelein, R. A., Hoek, L., & de Jong, C. A. F. (2011b). Hearing thresholds of a harbor porpoise (*Phocoena phocoena*) for helicopter dipping sonar signals (1.43-1.33 kHz) (L). *The Journal of the Acoustical Society of America*, *130*, 679-682. http://dx.doi.org/10.1121/1.3605541

Kastelein, R. A., Goodson, A. D., Lien, J., & de Haan, D. (1995). The effects of acoustic alarms on harbour porpoise (*Phocoena phocoena*) behaviour. In P. E. Nachtigall, J. Lien, W. W. L. Au, & A. J. Read (Eds.), *Harbour porpoises: Laboratory studies to reduce bycatch* (pp. 157-167). Woerden, The Netherlands: De Spil.

Kastelein, R. A., Hoek, L., de Jong, C. A. F., & Wensveen, P. J. (2010). The effect of signal duration on the underwater detection thresholds of a harbor porpoise (*Phocoena phocoena*) for single frequency-modulated tonal signals between 0.25 and 160 kHz. *The Journal of the Acoustical Society of America*, *128*, 3211-3222. http://dx.doi.org/10.1121/1.3493435

Kastelein, R. A., Janssen, M., Verboom W. C., & de Haan, D. (2005b). Receiving beam patterns in the horizontal plane of a harbor porpoise (*Phocoena phocoena*). *The Journal of the Acoustical Society of America*, *118*, 1172-1179. http://dx.doi.org/10.1121/1.1945565

Kastelein, R. A., Verboom, W. C., Jennings, N., & de Haan, D. (2008a). Behavioral avoidance threshold level of a harbor porpoise (*Phocoena phocoena*) for a continuous 50 kHz pure tone (L). *The Journal of the Acoustical Society of America*, *123*, 1858-1861. http://dx.doi.org/10.1121/1.2874557

Kastelein, R. A., Bunskoek, P., Hagedoorn, M., Au, W. W. L. & de Haan, D. (2002). Audiogram of a harbor porpoise (*Phocoena phocoena*) measured with narrow-band frequency-modulated signals. *The Journal of the Acoustical Society of America*, *112*, 334-344. http://dx.doi.org/10.1121/1.1508783; http://dx.doi.org/10.1121/1.1480835

Kastelein, R. A., de Haan, D., Goodson, A. D., Staal, C., & Vaughan, N. (1997). The effects of various sounds on a harbour porpoise (*Phocoena phocoena*). In A. J. Read, P. R. Wiepkema, & P. E. Nachtigall (Eds.), *The biology of the harbour porpoise* (pp. 367-383). Woerden, The Netherlands: De Spil.

Kastelein, R. A., de Haan, D., Vaughan, N., Staal, C., & Schooneman, N. M. (2001). The influence of three acoustic alarms on the behaviour of harbour porpoises (*Phocoena phocoena*) in a floating pen. *Marine Environmental Research*, *52*, 351-371. http://dx.doi.org/10.1016/S0141-1136(01)00090-3

Kastelein, R. A., Jennings, N., Verboom, W. C., de Haan, D., & Schooneman, N. M. (2006). Differences in the response of a striped dolphin (*Stenella coeruleoalba*) and a harbour porpoise (*Phocoena phocoena*) to an acoustic alarm. *Marine Environmental Research*, *61*, 363-378. http://dx.doi.org/10.1016/j.marenvres.2005.11.005

Kastelein, R. A., Steen, N., Gransier, R., Wensveen, P. J., & de Jong, C. A. F. (2012). Threshold received sound pressure levels of single 1-2 kHz and 6-7 kHz up-sweeps and down-sweeps causing startle responses in a harbor porpoise (*Phocoena phocoena*). *The Journal of the Acoustical Society of America*, *131*, 2325-2333. http://dx.doi.org/10.1121/1.3682032

Kastelein, R. A., Verboom, W. C., Jennings, N., de Haan, D., & van der Heul, S. (2008b). The influence of 70 and 120 kHz tonal signals on the behavior of harbor porpoises (*Phocoena phocoena*) in a floating pen. *Marine Environmental Research*, *66*, 319-326. http://dx.doi.org/10.1016/j.marenvres.2008.05.005

Kastelein, R. A., Verboom, W. C., Muijsers, M., Jennings, N. V., & van der Heul, S. (2005a). The influence of acoustic emissions for underwater data transmission on the behaviour of harbour porpoises (*Phocoena phocoena*) in a floating pen. *Marine Environmental Research*, *59*, 287-307. http://dx.doi.org/10.1016/j.marenvres.2004.05.005

Kastelein, R. A., Rippe, H. T., Vaughan, N., Schooneman, N. M., Verboom, W. C., & de Haan, D. (2000). The effect of acoustic alarms on the behavior of harbor porpoises (*Phocoena phocoena*) in a floating pen. *Marine Mammal Science*, *16*, 46-64. http://dx.doi.org/10.1111/j.1748-7692.2000.tb00903.x

Kastelein, R. A., Wensveen, P. J., Hoek, L., Au, W. W. L., Terhune, J. M., & de Jong, C. A. F. (2009). Critical ratios in harbor porpoises (*Phocoena phocoena*) for tonal signals between 0.315 and 150 kHz in random Gaussian white noise. *The Journal of the Acoustical Society of America*, *126*, 1588-1597. http://dx.doi.org/10.1121/1.3177274

Koschinski, S., Culik, B. M., Damsgaard Hendriksen, O., Tregenza, N., Ellis, G., Jansen, C., & Kathe, G. (2003). Behavioural reactions of free-ranging porpoises and seals to noise of a simulated 2 MW windpower generator. *Marine Ecology Progress Series*, *265*, 263-273. http://dx.doi.org/10.3354/meps265263

L-3 Oceans Group. (2007). *HELRAS DS-100 helicopter long-range active sonar*. Sylmar, CA: L-3 Oceans Systems. 2 pp.

Laake, J., Rugh, D., & Baraff, L. (1998). *Observations of harbor porpoise in the vicinity of acoustic alarms on a set gill net* (NOAA Technical Memorandum NMFS-AFSC-84). Washington, DC: U.S. Department of Commerce. 40 pp.

Lucke, K., Siebert, U., Lepper, P. A., & Blanchet, M. (2009). Temporary shift in masked hearing thresholds in a harbor porpoise (*Phocoena phocoena*) after exposure to seismic airgun stimuli. *The Journal of the Acoustical Society of America*, *125*, 4060-4070. http://dx.doi.org/10.1121/1.3117443

Madsen, P. T. (2005). Marine mammals and noise: Problems with root mean square sound pressure levels for transients. *The Journal of the Acoustical Society of America*, *117*, 3952-3957. http://dx.doi.org/10.1121/1.1921508

McDonald, M. A., Hildebrand, J. A., & Wiggins, S. M. (2006). Increases in deep ocean ambient noise in the Northeast Pacific west of San Nicolas Island, California. *The Journal of the Acoustical Society of America*, *120*, 711-718. http://dx.doi.org/10.1121/1.2216565

McDonald, M. A., Hildebrand, J. A., Wiggins, S. M., & Ross, D. (2008). A 50 year comparison of ambient ocean noise near San Clemente Island: A bathymetrically complex coastal region off Southern California. *The Journal of the Acoustical Society of America*, *124*, 1985-1992. http://dx.doi.org/10.1121/1.2967889

National Research Council (NRC). (2003). *Ocean noise and marine mammals*. Washington, DC: National Academic Press. 192 pp.

Olesiuk, P. F., Nichol, L. M., Sowden, M. J., & Ford, J. K. B. (2002). Effect of sound generated by an acoustic harassment device on the relative abundance of harbor porpoises (*Phocoena phocoena*) in Retreat Passage, British Columbia. *Marine Mammal Science*, *18*, 843-862. http://dx.doi.org/10.1111/j.1748-7692.2002.tb01077.x

Polacheck, T., & Thorpe, L. (1990). The swimming direction of harbor porpoises in relationship to a survey vessel. *Report of the International Whaling Commission*, *40*, 463-470.

Richardson, W. J., Greene, C. R., Jr., Malme, C. I., & Thomson, D. H. (1995). *Marine mammals and noise.* San Diego: Academic Press. 576 pp.

Teilmann, J., Tougaard, J., Kirketerp, T., Anderson, K., Labberté, S., & Miller, L. A. (2006). Reactions of captive harbor porpoises (*Phocoena phocoena*) to pinger-like sounds. *Marine Mammal Science*, *22*, 240-260. http://dx.doi.org/10.1111/j.1748-7692.2006.00031.x

Watts A. J. (Ed.). (2005). *Jane's underwater warfare systems* (17th ed., 2005-2006, pp. 119-121). Coulsdon, UK: Jane's Information Group.