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Quantifying Sound Exposure in a Pool: Comparing Hydrophones on a Grid with a Sound Recording Tag on a California Sea Lion (*Zalophus californianus*)

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Abstract

Investigating anthropogenic acoustic disturbance and sound exposure in marine mammals requires evaluation of experimental approaches used to measure the sound levels experienced by the subjects. In previous research, exposure of California sea lions (*Zalophus californianus*) to eight narrow noise bands was estimated as the mean sound pressure level (SPL) measured by hydrophones placed at multiple locations and depths in a pool. We compare this method of SPL estimation with SPLs measured with a sound recording tag ("D-tag"). Measurements were taken from (1) hydrophones at locations on a grid; (2) a D-tag at the same locations; (3) a D-tag attached in its housing to a harness on a sea lion swimming freely in the pool; (4) a D-tag in its housing in one position in the pool; (5) a D-tag on the sea lion in one position in the pool; and (6) a D-tag turning in one location in the pool without its housing, in its housing, and on the sea lion while she rotated on her body axis. The SPLs recorded by the D-tag on a free-swimming sea lion were ~8 to 10 dB lower than those measured by the grid hydrophones, and the differences varied by frequency. These differences in SPL are caused by a combination of the directionality associated with the D-tag itself, the presence of the housing, acoustic effects of the sea lion's body, and periods that the D-tag was out of the water during respirations. Measuring mean sound levels in test pools using hydrophones deployed on grids is valid; however, attaching tags to wild marine mammals may be more feasible than using hydrophone grids at sea. We summarize considerations when selecting a method to fit the design of future research.

Key Words: anthropogenic noise, directional sound reception, D-tag, exposure, flow noise, hydrophone, Otariidae, pinnipeds, sound shielding

Introduction

California sea lions (*Zalophus californianus*) are distributed in the eastern Pacific Ocean (Melin et al., 2018). They have acute underwater hearing between ~0.1 and 45 kHz (Reichmuth et al., 2013; Kastelein et al., 2023). Alongside naturally occurring underwater noise, California sea lions are exposed to underwater noise from anthropogenic activities at sea (Richardson et al., 1995), which can cause temporary or permanent hearing threshold shifts (TTS or PTS; Finneran, 2016). The resulting reductions in hearing sensitivity may constrain the detection of biologically relevant sounds by the sea lions. In the technical guidance by the National Oceanic and Atmospheric Administration (NOAA) aimed at avoiding noise-induced hearing injury to marine mammals in the coastal waters of the United States, allowable limits for underwater sound are expressed as frequency-weighted sound exposure levels (SELs; National Marine Fisheries Service [NMFS], 2018). The weighting depends on the marine mammal taxon of concern and is based on audiograms (graphs of sound detection threshold levels per frequency) and available TTS-onset SELs. The TTS-onset functions presently used for marine mammals exposed to underwater sound were based on the minimum SEL required to cause 6 dB TTS at each hearing frequency (Finneran, 2016; Southall et al., 2019). For otariids, the TTS information was derived from the one available study at the time with a California sea lion in which susceptibility to hearing damage by underwater fatiguing sounds (intended to cause TTS) of one frequency was tested (2.5 kHz; Kastak et al., 2005). Based on this data point and the underwater audiograms of the California sea lion (Reichmuth et al., 2013) and other otariids, Finneran (2016) and Southall et al. (2019) proposed a weighting function for otariids for underwater sound.

A series of studies conducted subsequently to increase the number of TTS-onset data for California sea lions showed that the species is more susceptible to underwater sound than was previously believed (Kastelein et al., 2021, 2022a, 2022b, 2024, 2025). The research also revealed differences in methods used and TTS-onset data collected by Kastak et al. (2005) and Kastelein et al. (2021, 2022a, 2022b, 2024, 2025). Accurate and repeatable estimation of the SPLs that otariids are exposed to during research on TTS is essential for the development of weighting functions and regulations that are needed for the effective protection of otariids.

Regulatory criteria are based on TTS studies conducted in pools and net pens, so it is important to verify, or adapt, the SELs used in the previous TTS studies with California sea lions conducted in the same pool (Kastelein et al., 2021, 2022a, 2022b, 2024, 2025). In these studies, the mean SPL was derived from grid measurements and the swimming patterns of the sea lions during the exposures. Observations showed that this was a valid approach, though if subjects are able to favor parts of the pool where SPL is lowest, the mean received SPL based on all the grid measurements may be an overestimation of the mean SPL they received. The development of sound recording tags (digital acoustic recording tag, "D-tag"; Johnson et al., 2009; Shorter et al., 2017) made it possible to record the SPL experienced by a moving subject. Captive subjects can be trained to carry D-tags on harnesses; other methods have been used to attach them to wild marine mammals, such as suction cups for cetaceans that have a smooth skin (Miller et al, 2012, 2014; Holt et al., 2021) and glue for pinnipeds that have hair (Mikkelsen et al., 2019; Nachtsheim et al., 2023).

The goal of the present study was to compare the mean SPL that a free-swimming California sea lion in a pool is exposed to, as measured in previous TTS studies via hydrophones on a grid (Kastelein et al., 2021, 2022a, 2022b, 2024, 2025), with SPLs measured with a D-tag attached in its housing to a harness on the back of a free-swimming sea lion, and to explain the differences in the measurements. To do this, after initial calibrations of the D-tag in three rotational planes, measurements of SPL (and, in some cases, spectra) were taken from (1) hydrophones on a grid in a pool; (2) a D-tag on the same grid; (3) a D-tag on a sea lion while she swam freely in a pool (with sound produced at three levels); (4) a D-tag in its housing in one position in a pool (sound produced at three levels); (5) a D-tag on a sea lion in one position in a pool; and (6) a D-tag turning in one location in a pool without its housing, in its housing, and on the sea lion while she rotated on her body axis. Also, the linearity of recordings from the D-tag was tested, both in one location in the water column and when the D-tag was attached to a free-swimming sea lion. An iterative process was used during the study to decide which tests to conduct to achieve the goals.

Recommendations are provided for research using hydrophone grids and linear arrays or recording tags in pools and net pens to investigate acoustic disturbance in the wild. The results can be used to improve tag design and placement, as well as for modelling and analysis of data from sound recording tags.

Methods

Study Animal and Study Area

The subject was a healthy, adult female identified as California sea lion F01. During the study (between June 2022 and July 2023), she was 11 to 12 y old, her total body length was 165 cm, her girth at the D-tag location was 102 cm (32 cm diameter), and her body weight was around 77 kg.

The study was conducted at the SEAMARCO Research Institute, the Netherlands, in a remote and quiet location. The California sea lion was kept, and the study was conducted, in a pool complex consisting of an outdoor pool (7 × 4 m, 2 m deep), connected via two channels (each 2 × 2 m, 1 m deep) to an indoor pool. The indoor pool consisted of a deep part (6 × 4 m, 2 m deep, used for previous TTS studies) in which the SPL measurement tests were conducted, and an adjacent shallow area (6 × 3 m, 1 m deep) in which the transducers were housed (for more details of the facility and a top view of the pool complex, see Kastelein et al., 2021). The water circulation system was switched off at least 1 h before the sound measurements were conducted, further reducing background noise, and the sea lion was confined to the deep part of the indoor pool during measurements when she was wearing the harness. The shallow and deep parts of the pool were separated by a net. One corner of the pool was not accessible to the sea lion (Figure 1).

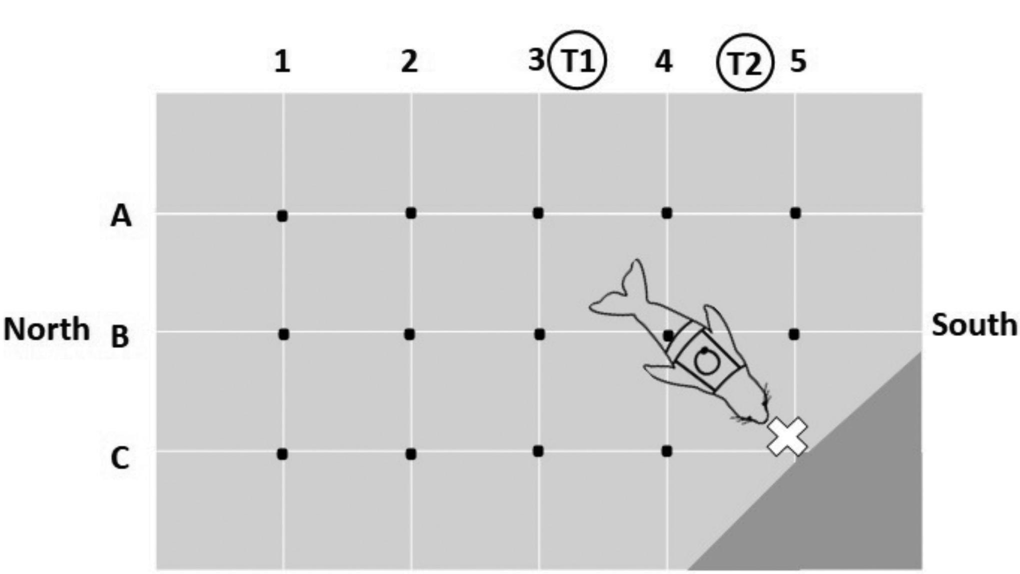


Figure 1. Top view of the 2 m-deep part of the 6 × 4 m indoor pool, showing the measurement grid, the area not accessible to the California sea lion (*Zalophus californianus*; dark grey triangle), and locations of the EDO 337 transducer (T1; used for the noise bands at 32 and 40 kHz) and the Lubell LL1424HP transducer (T2; used for the noise bands at 0.6 to 16 kHz), both at 1 m depth. Measurements were made at each of the 14 locations on the grid (indicated with black dots), with two B&K 8106 hydrophones and the D-tag, at two depths (0.1 and 1.0 m below the water surface). The white x indicates the listening station location (at 1 m depth) where the sea lion positioned herself so that the D-tag was close to grid location B4 (as shown). When she was swimming freely during sound exposures, the sea lion generally swam clockwise ovals in the light grey area.

Acoustics

Sounds Measured—Eight continuous (i.e., 100% duty cycle), one-sixth-octave noise bands (NBs), centered at 0.6, 1, 2, 4, 8, 16, 32, and 40 kHz (underwater wavelengths of 250, 150, 75, 38, 19, 9, 5, and 4 cm, respectively, assuming a speed of sound in seawater of 1,500 m/s), all without harmonics, were used for the sound exposures. The frequencies were selected because they were within the hearing range of California sea lions (Reichmuth et al., 2013; Kastelein et al., 2023), and because they were used as fatiguing sounds in the previous series of TTS studies with California sea lions by SEAMARCO (Kastelein et al., 2021, 2022a, 2022b, 2024, 2025). The digitally generated sounds (WAV files; sample rate: 768 kHz) were played back by a laptop computer (Acer Aspire Model V5-552; Acer, Taipei, Taiwan) with a program written in *LabVIEW* to an external data acquisition card (National Instruments Model USB 6361; National Instruments, Austin, TX, USA), the output of which could be controlled in 1 dB steps with the *LabVIEW* program. The output of the card went through a custom-built buffer to a custom-built passive low-pass filter, after which the NBs centered at 0.6 to 16 kHz went to a power amplifier (HQ Model VPA2200MBN; Velleman, Gavere, Belgium), which drove the transducer (Lubell Model LL1424HP; Lubell Labs, Columbus, OH, USA) through an isolation transformer (Lubell Model AC1424HP, Lubell Labs). The NBs centered at 32 and 40 kHz went through a custom-built, high-frequency power amplifier (L7) and were projected in the pool with a toroidal beam transducer (EDO Model 337; EDO Corporation, Salt Lake City, UT, USA). Both transducers were placed in the shallow part of the pool at 1 m depth, 5 cm above the pool floor, near the edge of the deep part of the pool. The linearity of the transmission system producing the NBs was regularly checked and was found to be consistent to 1 dB within a 42 dB range (overlapping the SPL range used in the present study).

Before each sound exposure test with a D-tag on the California sea lion or SPL measurement with a D-tag alone, the voltage output of the emitting systems to the transducer and the voltage output of the sound-receiving system were checked with a voltmeter (Gw Instek Model GES927216GMD-8341; Good Will Instruments, Taipei, Taiwan) by producing a continuous tone from the laptop. The underwater acoustic signal was checked with a hydrophone (Reson Model EC6073; Teledyne Marine Technologies, Houston, TX, USA) located at the listening station (Figure 1), a pre-amplifier (Model

2365; Brüel & Kjaer [B&K], Virum, Denmark), and a spectrum analyzer (Model PCSU1000, Velleman). If the values obtained were the same as those obtained during SPL calibrations (see next section), the SPLs were assumed to be correct, and a sound measurement test with the D-tag was performed.

Hydrophones Used to Measure Sound Pressure Level (SPL)—The ambient noise was measured, and the NBs were calibrated several times during the study period by TNO. The sound measurement equipment used for this consisted of two omnidirectional hydrophones (B&K Model 8106, sensitivity -173 dB re 1 V/µPa; both were used at the same time) with a multichannel high-frequency analyzer (B&K PULSE, Model Lan-XI Type 3160) and a laptop computer with B&K PULSE software (*Labshop*, Version 12.1). The system was calibrated with a pistonphone (B&K Model 4223). The mean SPL of the NBs was determined over a period of 10 s. A correction for the frequency-dependent sensitivity of the calibrated B&K 8106 hydrophones was applied for the higher frequencies (32 and 40 kHz).

D-tag, Housing, and Harness—SPL measurements were made with a high-resolution, motion-sensing digital acoustic recording tag (D-tag, University of Michigan, Ann Arbor, MI, USA). The D-tag (Version 3; s/n 329C) was 9 cm in length, 6 cm in width, and 3 cm in height; in air, it weighed 150 g. The D-tag had two channels, each composed of two custom-made integrated hydrophones and a preamplifier, and both connected to a stereo recorder (Shorter et al., 2017). The distance between the center of the two hydrophones was 4 cm (Figure 2a). Only recordings via hydrophone 1 were used in the present study (in the D-tag we used, hydrophone 1 was more sensitive than hydrophone 2, by ~6 dB, measured at 0.6, 1, and 4 kHz). Sample rate was generally set at 120 kHz; it was set at 240 kHz when the D-tag was being rotated vertically so that the 70 and 90 kHz position-indicating tones could also be recorded (see below).

A plastic housing for the D-tag was made with a 3-D printer. The housing was 2 to 6 mm thick, depending on location, and had two openings through which the two hydrophones protruded (Figure 2b). The housing containing the D-tag was attached to the back of the California sea lion by means of a harness. The harness consisted of straps with a rectangular piece of plastic canvass (30 × 40 cm) to which the plastic base plate (5 mm thick) of the housing was riveted. The combined weight of the harness, housing, and D-tag in air was 1,100 g. The harness could be attached to the sea lion by means of three snap hooks. The straps formed a loop around the sea lion's neck and a loop below each of her pectoral fins. When the harness was on the sea lion, the D-tag was dorsal of the rostral tip of her lungs, and the hydrophones were facing towards her back (caudal) and left/right sides (lateral; Figure 3). The study animal was trained, using positive reinforcement, for 6 mo to accept the harness voluntarily. It was placed on her a few minutes before each session in which she was exposed to sound.

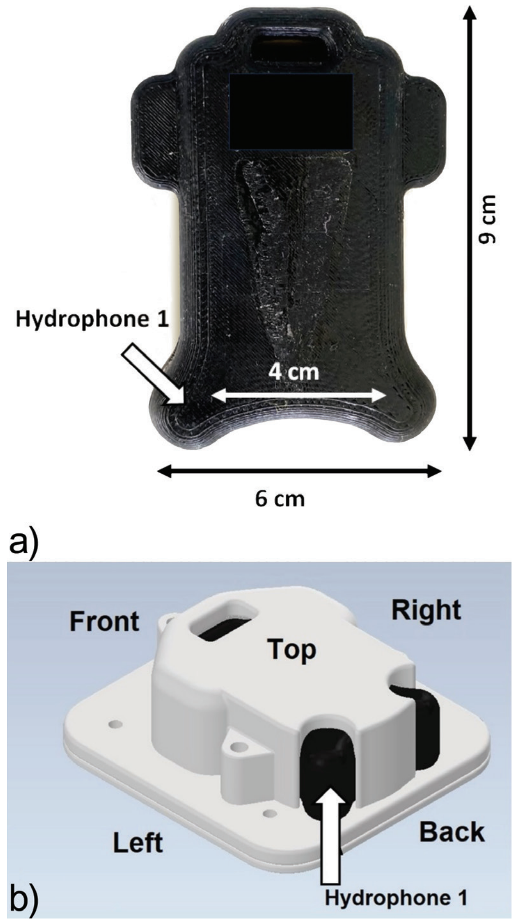


Figure 2. The D-tag (a) without its housing (height: 3 cm); and (b) the D-tag in a horizontal position inside its housing, which was riveted to the harness. The hydrophones (in black) protruded through openings in the housing. Only hydrophone 1 was used in the study. The distance between the center of the two hydrophones was 4 cm. The plastic base plate in (b) was 10 × 10 cm and 5 mm thick. The housing shown in this figure is white, but black housing was used in the study (see Figure 3).

Calibrations of the D-Tag in Three Rotational Planes, with Results—Measurements of SPLs from the D-tag in its housing, rotating in one location,

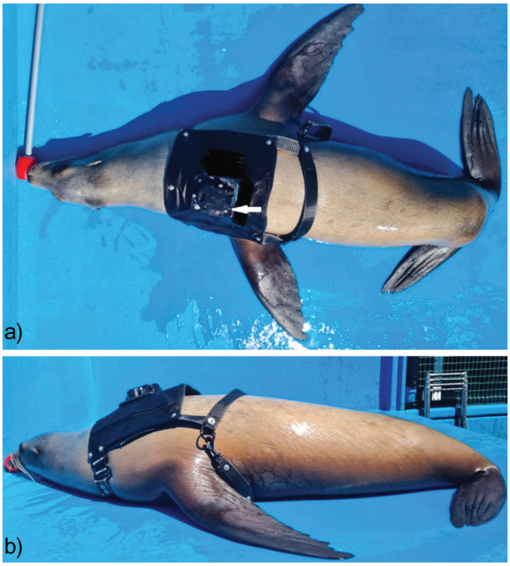


Figure 3. The sound-recording D-tag, housing, and harness, attached to the California sea lion with snap hooks: (a) dorsal view of the D-tag location on the body, showing the two hydrophones protruding from the housing (hydrophone 1, used in the study, is indicated with an arrow; it is on the left side of the tag at the back); and (b) lateral view, showing the height of the D-tag in its housing in relation to the sea lion's body.

were conducted to calibrate the D-tag and determine the directivity of hydrophone 1 because when it was attached to the California sea lion, the D-tag was expected to be in various positions relative to the underwater transducers. To assess the directionality of sound measurement via D-tags in the vertical, horizontal, and rotational planes in a reverberant sound field, a D-tag in its housing with the plastic base plate fixed to a 10 × 15 cm wooden base (18 mm thick), which was attached to a wooden pole, was placed in location B4 (Figure 1) at a distance of ~2 m from either the Lubell LL1424HP transducer or the EDO 337 transducer at 1 m depth (the depth of the transducers). Each NB was played at one source level (SL) while the D-tag was rotated (in four 90° steps: 0°, 90°, 180°, 270°, and back to 0°/360°) in three planes: (1) horizontal, (2) vertical, and (3) rotational (see photos in Figure 4). In each position, a different pure tone was played for 1 s from another transducer connected to a wave generator (Agilent Model 33120 A; Hewlett Packard, Palo Alto, CA, USA) to code the position of the D-tag in each plane. This tone was used as an acoustic reference of the position in the later analysis of the sound recording on the D-tag.

The received SPLs of the D-tag hydrophone system were calibrated by comparing the amplitudes in the WAV file recordings to amplitudes of recordings made of known SPLs that were measured using the B&K 8106 hydrophones. The hydrophone sensitivity measures are presented in dB re 1 V/µPa but should be interpreted as an all-in-one calibration factor from digital waveform to SPL. This was repeated for every discrete angle for each orientation. In Figure 4, the sensitivity of the D-tag within the housing at different orientations was normalized to the sensitivity at 0°. With internal gain set to 0, the sensitivity at 0° was between -182 and -176 dB re 1 V/µPa, depending on the frequency and orientation.

When the D-tag within its housing was rotated in the horizontal plane, the SPL that was measured varied in a frequency-dependent way, but no pattern emerged as the frequency increased (Figure 4a). Most variation was found in recordings of NBs centered at 2 and 16 kHz. The SPL of the NB at 2 kHz was greatest when the D-tag was in the 90° position, with hydrophone 1 partially shielded by the D-tag relative to the sound source. The SPL of the NB at 16 kHz was reduced by ~5 dB when hydrophone 1 was partially (90°) and fully (180°) shielded by the D-tag. In rotation in the horizontal plane at 180°, hydrophone 1 was shielded by the housing and the D-tag itself.

When rotating the D-tag in its housing in the vertical plane, the SPL that was measured varied in a frequency-dependent way (Figure 4b). Most variation was found in recordings of NBs centered at 2, 4, and 16 kHz. At NBs centered at 2 and 4 kHz, the SPL was increased when hydrophone 1 was partially (90°) and fully (180°) shielded by the D-tag relative to the sound source. With the NB at 16 kHz, the SPL decreased by around 7 dB when hydrophone 1 was partially (90°) and fully (180° and 270°) shielded by the D-tag. In rotation in the vertical plane at 180°, hydrophone 1 was shielded by the wooden base, the housing, and the D-tag itself.

When rotating the D-tag in the rotational plane, the measured SPL also varied in a frequency-dependent way (Figure 4c), but the variation in SPL was small (≤ 3 dB). The rotation mainly caused the SPL to decrease relative to the 0°/360° position. In all positions in the rotational plane, there were no objects or parts of the housing or D-tag itself blocking the sound pathway at any angle.

Experimental Procedures and Methods

SPLs Measured with the Hydrophones and D-Tag on a Grid—The SPLs of the NBs were measured at 28 grid point locations in the pool: at 14 locations on a horizontal grid with cells of 1 × 1 m, at two depths per location (0.1 and 1.0 m below the surface; Figure 1). Each of the eight NBs was produced at one SL. Measurements were taken with the B&K

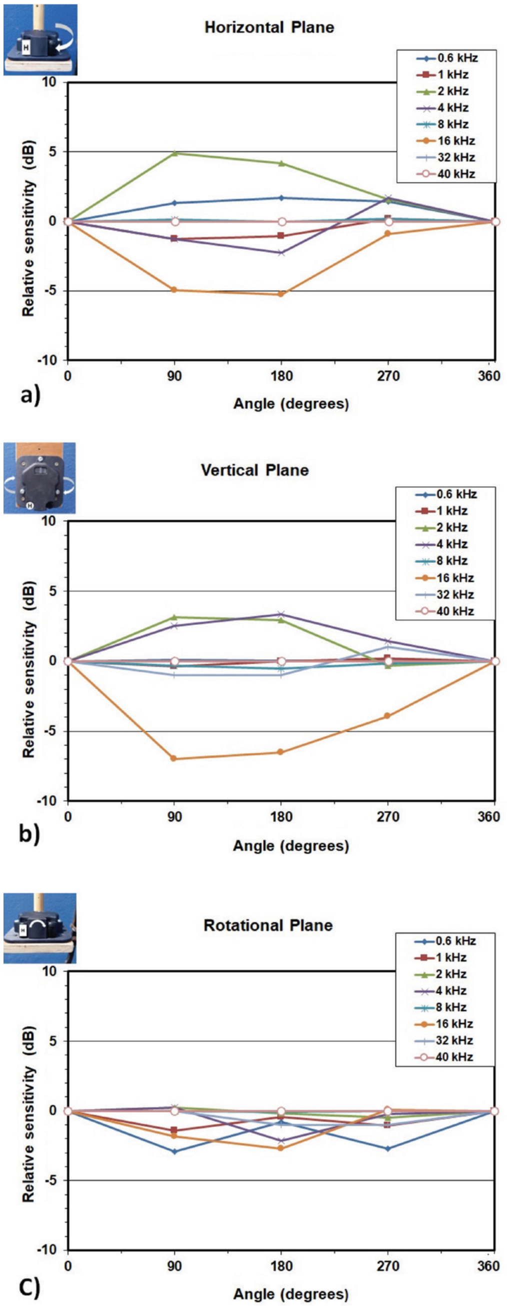


Figure 4. Relative sensitivity of hydrophone 1 of the D-tag for the one-sixth-octave noise bands centered at 0.6, 1, 2, 4, 8, 16, 32, and 40 kHz, while the D-tag was rotated in four positions (0° is the same as 360°) in the (a) horizontal, (b) vertical, and (c) rotational planes. The photos were taken from the location of the transducer with the D-tag in the 0°/360° position; H = hydrophone 1. Sensitivities are normalized per frequency to the 0°/360° position (i.e., the position shown in the photos).

8106 hydrophones hanging in a vertical position, and with the D-tag in its housing fixed by the plastic base plate to the horizontal wooden base attached to a structure made from water-filled, 32-mm diameter polyvinyl chloride (PVC) tubes. This structure was suspended on a string; another string prevented the structure from moving around its axis and thus kept the back of the D-tag with the hydrophones pointing towards the southern end of the pool (Figure 1). When the structure was moved through the pool, the direction of the D-tag was constant, and therefore its angle in relation to the transducer varied. The D-tag was placed horizontally to replicate its most common position on the sea lion while she was swimming freely in the pool (Figure 3b).

Each of the 28 grid point locations was indicated by a coded pure tone (between 6 and 39 kHz) that was used as a reference during analysis of the recordings. At each location, the SPL of each NB was measured for 10 s. The SPLs were calculated by averaging the squared sound pressure of the signal over each recording length. A correction for the frequency-dependent sensitivity of the calibrated B&K 8106 hydrophones was applied for the higher frequencies.

SPLs Measured via the D-Tag on the Free-Swimming California Sea Lion—With the California sea lion swimming freely in the pool, wearing the harness with the D-tag in its housing, one of the eight NB frequencies was switched on for 10 min, after which the frequency was changed. In each 30-min session, three NB center frequencies were tested. During the study, each NB center frequency was tested during two 10-min periods in two sessions. Each NB center frequency was tested at one SL.

At each NB frequency, measurements were also carried out at three SLs to assess the linearity of the SPLs recorded when the D-tag was on the California sea lion's back. With the sea lion swimming freely in the pool, wearing the harness with the D-tag, each NB frequency was switched on for 10 min at the SL that had been used initially. After 10 min, the SL was reduced by 6 dB for 10 min, after which the SL was reduced by another 6 dB for 10 min. Thus, in each session lasting 30 min, three SLs of one NB frequency were tested.

The mean SPL for each NB was calculated by averaging the squared sound pressure over the 10-min recording. To obtain percentiles, the SPLs were also calculated over 125 ms intervals. This interval was selected to capture the brief moments when the California sea lion surfaced, which resulted in sharp drops in the SPL. The previously calibrated amplitudes of the D-tag WAV files measured at 0°/360° in the horizontal plane (see photo in Figure 4a) were used to calculate the SPLs, as this position corresponded to the sea lion's most common posture when swimming. During sound exposure, the sea lion's swimming behavior, pattern, and respirations were recorded on video using a camera with a wide-angle lens from above the water surface (top view).

SPL Measured with the D-Tag in Its Housing in One Position—SPL was measured with the D-tag in its housing in one position in the pool to determine the linearity of the D-tag hydrophone without shielding caused by parts of the California sea lion's body. The D-tag, in its housing and on its wooden base, was attached to a wooden pole (at 0°/360° in the horizontal plane; see photo in Figure 4a) at 1 m depth with the back of the D-tag pointing east, towards the transducers (at location B4; Figure 1). Each of the eight NB frequencies was produced at three SLs (6 dB steps). The mean SPL per level was measured over 60 s.

SPLs Measured with the D-Tag on the California Sea Lion in One Position—SPL measurements with the D-tag attached to the stationary California sea lion were done to investigate variation caused by shielding by parts of the sea lion's body with little change in the position of the D-tag relative to the transducers. The sea lion, wearing the harness and the D-tag in its housing, was trained to position her nose at the listening station (indicated by the white x in Figure 1 and also used in the previous TTS studies; Kastelein et al., 2021, 2022a, 2022b, 2024, 2025) at the same depth as the transducers (1 m below the surface). In this position, the D-tag was close to grid location B4 with its back and left side (with hydrophone 1) pointing east, towards the transducers (Figure 1). When the sea lion arrived at the listening station, a 1-s 70 kHz tone was produced; and when she left the station after about 10 s, a 1-s 90 kHz tone was produced. These tones, inaudible to the sea lion, marked the analysis period over which the mean SPL was calculated. The sea lion was sent to the listening station four times for each NB frequency. Each NB frequency was produced at one SL, and the sound was on during the entire session. The average SPL of the NB was calculated by averaging the squared sound pressure of the signal over the ~10 s recording. The previously calibrated amplitudes of the D-tag WAV files measured at 0°/360° in the horizontal plane (Figure 4a) were used to calculate the SPLs.

SPLs Measured with the Turning D-Tag—Measurements were taken from the D-tag turning vertically on its axis at location B4 in the pool (see photo in Figure 4b), without its housing, in its housing, and in its housing on the harness on the California sea lion. The wooden base and wooden pole were not used. The D-tag was held in the vertical position at 1 m depth, with its back facing the pool floor.

Firstly, tape was used to attach the D-tag, without its housing, to a water-filled, 32-mm diameter PVC tube. SPL was measured via the D-tag while it was turned around on its axis manually. The PVC tube was turned around by using a fixed tubular mount above the water surface to ensure precise positioning of the D-tag. The start of a turn was marked with a 1-s 70 kHz tone and the end by a 1-s 90 kHz tone, both produced with a sound generator and an underwater transducer. A full circle took on average ~15 s (range: 13 to 19 s).

Secondly, the D-tag was placed in its housing and then attached to the water-filled, 32-mm PVC tube that was turned around on its axis as described above. Again, tones were used to mark the analysis period, and SPL measurements were taken, as described above. This was done to determine potential effects of the housing. A full circle took on average ~14 s (range: 11 to 18 s).

Thirdly, the D-tag, in its housing, was attached by means of the harness to the California sea lion while she rotated on her body axis to determine the shielding effect of the sea lion's body. The sea lion was trained to position herself vertically in the water column, with her head just above the water surface and her nose touching a target (a float on a pole held by a trainer ~30 cm above the water surface at location B4; Figure 1). In this start position, the sea lion's back, and thus the top of the attached D-tag, was facing the transducer in the 0°/360° vertical position (with the back of the D-tag pointing towards the pool floor, at ~1 m depth; see photo in Figure 4b). On a vocal command, the sea lion slowly turned around on her body axis in a clockwise direction when viewed from above. A full circle took on average ~13 s (range: 6 to 18 s). As above, tones that were inaudible to the sea lion were used to mark the start and end of each turn. The sea lion did the rotation three times for each NB.

For all three measurements, each NB was produced at one SL, and the sound was on during the entire session. From the moment the rotation started, the SPLs of the NB were calculated over every 125-ms time interval during one full rotation. The D-tag sensitivity measured at 0°/360° in the vertical plane (Figure 4b) was used to convert signal voltage levels into SPLs. It was assumed that the rotational speed was constant between the start and end of one rotation. With this assumption, the rotational angle was calculated every 125 ms by interpolation.

Table 1. Hydrophones and D-tag on a grid: the mean (± standard deviation) sound pressure level (SPL) per depth (0.1 and 1.0 m) of one-sixth-octave noise bands (NBs), centered at 0.6, 1, 2, 4, 8, 16, 32, and 40 kHz, measured at 14 locations in the pool with two B&K 8106 hydrophones and with a D-tag in its housing (in a fixed north-south position, with the back of the D-tag facing south; Figure 1). Means are calculated with *n* = 14 locations per depth (see Figure 1). The source level, and thus the recorded SPL, varied per NB center frequency.

NB center frequency (kHz)	Mean ± standard deviation SPL (dB re 1 µPa); *n* = 14			
	0.1 m depth		1.0 m depth	
	B&K 8106 hydrophone	D-tag	B&K 8106 hydrophone	D-tag
0.6	156 ± 4	153 ± 5	165 ± 3	163 ± 5
1	142 ± 3	144 ± 2	150 ± 2	149 ± 2
2	151 ± 4	148 ± 3	153 ± 3	154 ± 3
4	151 ± 2	146 ± 2	152 ± 1	150 ± 1
8	145 ± 4	143 ± 1	144 ± 3	143 ± 0
16	163 ± 2	159 ± 3	159 ± 1	158 ± 2
32	153 ± 2	149 ± 1	150 ± 2	149 ± 1
40	135 ± 2	139 ± 0	137 ± 4	139 ± 0

Results

SPLs Measured with Hydrophones and a D-Tag on the Grid, and with a D-Tag on the Free-Swimming California Sea Lion

Measurements taken on the grid revealed that the mean SPL per NB and per depth (*n* = 14) measured with the B&K 8106 hydrophones and with the D-tag differed by 2 to 5 dB at 0.1 m depth and by 1 to 2 dB at 1.0 m depth. In 12 of the 16 cases, the mean SPLs measured with the D-tag were lower than the mean SPLs measured with the B&K 8106 hydrophones (Table 1). The 10-min recordings made via the D-tag attached to the free-swimming California sea lion showed approximately constant SPLs with short ~40 dB drops in level coinciding with surfacings, mostly for breathing; when the D-tag was in air, the SPL was limited by electronic noise of the tag (Figure 5).

The L_{90} (90th exceedance SPL) is the SPL above which the mean SPL (calculated over 125 ms intervals) falls during 90% of the swimming time. This value was most affected by gaps in the sound exposure which occurred when the animal was breathing, as it depended on the total time spent at the surface by the D-tag within the 10-min recording time. The L_{10} (10th exceedance SPL) is the SPL above which the mean SPL falls during 10% of the swimming time. This value depended on the time spent completely underwater by the D-tag.

The swimming pattern of the California sea lion differed between sessions, but she typically swam in clockwise ovals, moving closer to and farther away from the transducer while changing her orientation in relation to it. This pattern was evident in the variation in SPL recorded by the D-tag. With NBs at 32 and 40 kHz, the peak and trough SPLs matched L_{10} and L_{90} very closely (Figure 5).

The mean SPLs over 10-min periods measured with the D-tag attached to the California sea lion are compared to measurements from hydrophones and the D-tag on the grid in Table 2. The values between each of the two sessions in which the D-tag was attached to the sea lion differed by only 0 to 2 dB, depending on the NB center frequency, despite, sometimes large, differences in the number of respirations (which accounted for short gaps in sound exposure; Figure 5; Table 2). The mean SPL recorded with the D-tag on the free-swimming sea lion was ~8 to 10 dB lower than the mean SPL recorded with hydrophones and D-tags on the grid (Table 2).

SPLs Measured for Three Source Levels

The mean SPL of each NB was compared at three SLs, as measured by the D-tag in its housing both on the free-swimming California sea lion and in one position in the pool (horizontal, with its back facing the transducers, in location B4; Figure 1). With the D-tag on the swimming sea lion, when the SL was reduced by 6 dB, the mean SPL recorded by the D-tag dropped by between

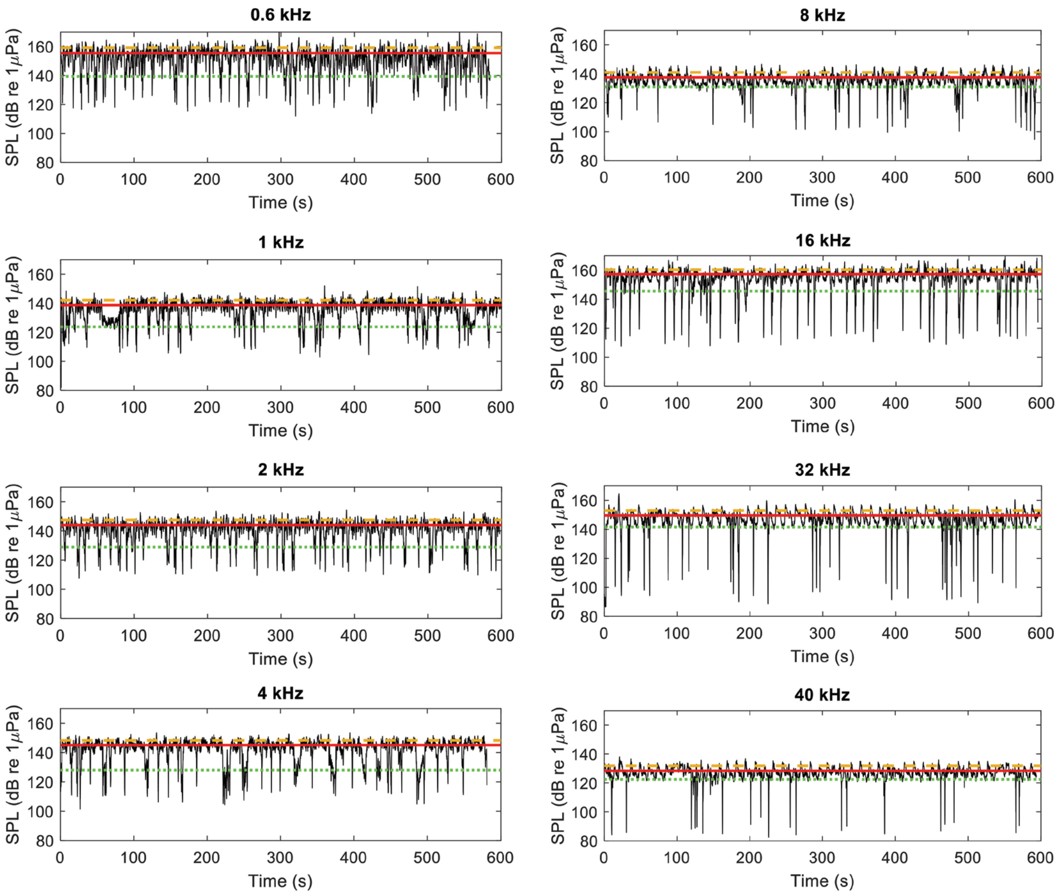


Figure 5. Sound pressure level (SPL) variations over time (10 min) for each noise band center frequency (0.6, 1, 2, 4, 8, 16, 32, and 40 kHz), as recorded via the D-tag attached, in its housing on a harness, to the back of the free-swimming California sea lion in the pool, in the first of the two sessions conducted for each center frequency (the second sessions differed mainly in the numbers of respirations; see Table 2). The brief drops in SPL are due to surfacings, which mostly coincided with respirations. Also shown are the mean SPL (calculated over 125 ms intervals; solid red line), L_{90} (the SPL that is exceeded 90% of the time; green dotted line), and L_{10} (the SPL that is exceeded only 10% of the time; orange dashed line).

2.7 to 6.7 dB, depending on the NB center frequency. When the SL was reduced by 12 dB, the mean SPL dropped by between a further 4.0 to 6.6 dB, depending on the NB center frequency (Figure 6a). With the D-tag in one position in the pool, when the SL was reduced by 6 dB, the mean SPL recorded by the D-tag dropped by 4.8 to 6.1 dB, depending on the NB center frequency. When the SL was reduced by 12 dB, the mean SPL dropped by between a further 5.5 to 6.3 dB, depending on the NB center frequency (Figure 6b). Thus, the linearity was generally good, except for the NB at 16 kHz (both with the D-tag in one position and on the free-swimming sea lion), therefore these measurements were repeated, but yielded the same results.

SPLs Measured with the D-Tag on the California Sea Lion in One Position

The variation in mean SPL measured by the D-tag when the California sea lion positioned herself four times at the listening station in the pool was small: 0 to 4 dB, depending on the NB center frequency (Table 3). The spectra of the NBs measured via the D-tag on the sea lion in one position in the pool were compared with those measured by the D-tag on the free-swimming sea lion (Figure 7). The difference in SPLs between the NB frequencies was influenced by the directionality of the D-tag but was similar for each of the eight NBs in both cases (i.e., D-tag on the sea lion in one position, or D-tag on the free-swimming sea lion). The measurements from one position for the NBs at 0.6, 1, and 2 kHz

Table 2. The mean sound pressure level (SPL; over 10 min) recorded via the D-tag attached to the California sea lion (*Zalophus californianus*) swimming freely in the pool during two sessions (results of each session shown separated by a comma), with the L_{90}, L_{50}, and L_{10} (analysis window 125 ms; 90th, 50th, and 10th exceedance SPLs: the SPLs above which the mean SPL falls during 90, 50, and 10% of the swimming time). The number of respirations in each 10-min session with the free-swimming sea lion is shown in parentheses after the mean SPL of that session. Also shown are the mean (± standard deviation) SPLs recorded in the pool with two hydrophones (B&K 8106) on a grid, and with the D-tag on the grid. The grid measurements are averaged for the 14 locations and two depths ($n = 28$; Figure 1). The source level, and thus the recorded SPL, varied with the noise band (NB) center frequency.

NB center frequency (kHz)	D-tag on free-swimming California sea lion				Hydrophones (B&K 8106) on a grid, mean SPL (dB re 1 µPa)	D-tag on a grid, mean SPL (dB re 1 µPa)
	Mean SPL (dB re 1 µPa)	L_{90} (dB re 1 µPa)	L_{50} (dB re 1 µPa)	L_{10} (dB re 1 µPa)		
0.6	155 (44), 153 (46)	139, 138	153, 151	159, 157	163 ± 7.1	162 ± 6.8
1	139 (37), 138 (25)	124, 124	138, 136	142, 140	148 ± 5.0	148 ± 3.3
2	144 (44), 146 (38)	129, 130	143, 144	148, 149	153 ± 3.6	153 ± 4.1
4	145 (35), 146 (40)	128, 128	144, 144	148, 148	152 ± 1.8	149 ± 2.5
8	137 (30), 137 (40)	131, 131	136, 135	141, 140	146 ± 3.1	143 ± 0.5
16	157 (47), 158 (34)	146, 145	156, 155	160, 161	162 ± 2.7	160 ± 2.6
32	151 (34), 151 (22)	142, 144	148, 149	153, 154	152 ± 2.4	149 ± 1.2
40	128 (23), 128 (12)	123, 123	127, 128	132, 130	138 ± 3.5	139 ± 0.2

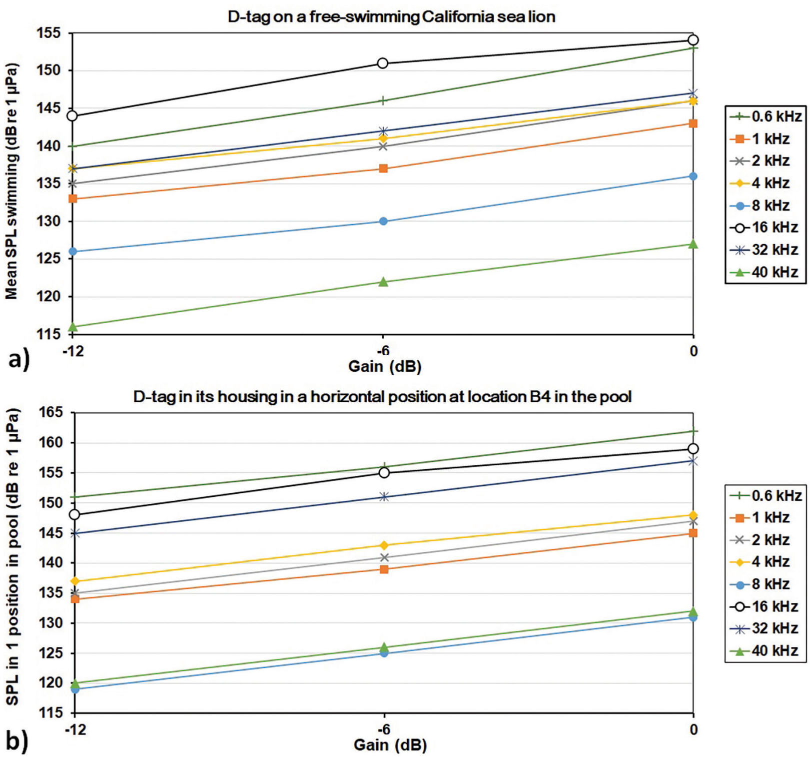


Figure 6. Checking the linearity of the recordings at eight noise band center frequencies (0.6 to 40 kHz), with three source levels (gains) differing by 6 dB, with (a) the D-tag on a free-swimming California sea lion (mean SPL recorded by the D-tag during 10-min periods), and (b) the D-tag in its housing in a horizontal position at location B4 in the pool (Figure 1) at 1 m depth, with the back of the D-tag pointing towards the transducers (mean SPL over 1-min periods). The linearity was generally good, except for the NB at 16 kHz.

Table 3. The mean SPL (± standard deviation [SD], and measured over ~10 s) recorded by the D-tag while the California sea lion was stationary at the listening station (*n* = 4; see Figure 1). The sea lion was horizontal at 1 m depth, and the D-tag was in its housing, attached to the harness, with its back, and therefore the hydrophone, facing the transducer. All four measurements at 8 kHz were identical (SD = 0). The source level, and thus the recorded SPL, varied with the noise band (NB) center frequency.

NB center frequency (kHz)	Mean (± SD) SPL (dB re 1 µPa)	SPL range (dB re 1 µPa)
0.6	158 ± 1.7	156-160
1	144 ± 1.5	143-146
2	142 ± 1.5	141-144
4	150 ± 1.5	148-151
8	135 ± 0.0	135
16	161 ± 0.8	160-162
32	159 ± 1.0	157-159
40	132 ± 0.5	132-133

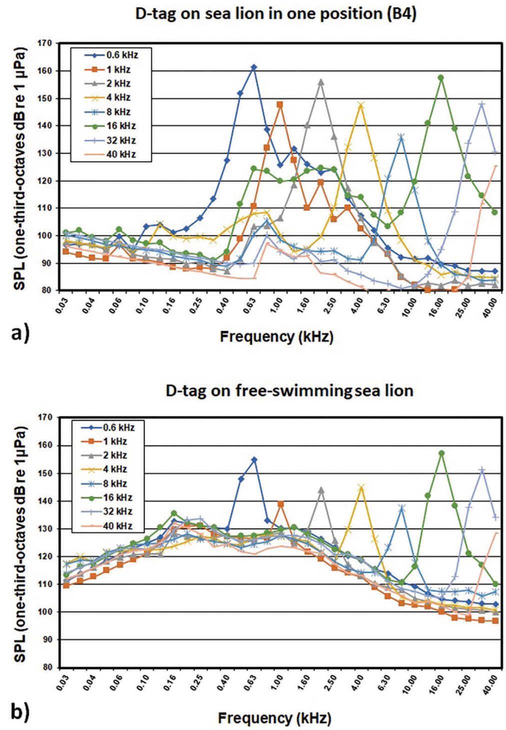
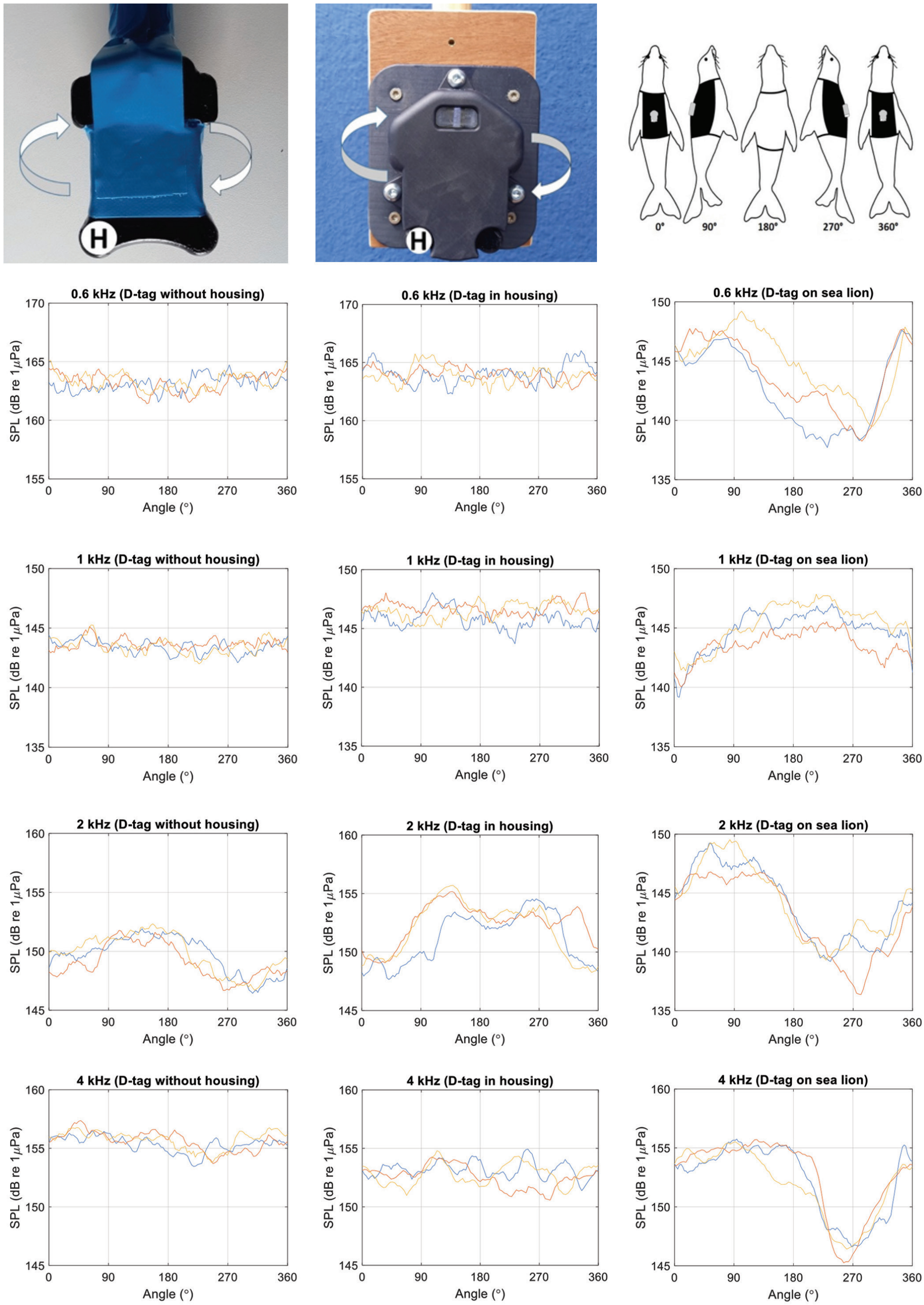


Figure 7. The mean sound pressure level (SPL) at each frequency measured with the D-tag on the California sea lion in one position, at location B4 in Figure 1 (a), and with the D-tag on the sea lion swimming freely in the pool (b). The flow noise shown in (b) contained energy over the entire measurement bandwidth, but it was so low that it did not affect the recorded SPLs of the noise bands (NBs). The source level, and thus the recorded SPL, varied with NB center frequency. The increased level between 0.4 and ~5 kHz for the 16 kHz sound in (a) was due to the transmission system; it was also seen in the recordings with the B&K 8106 hydrophones.

were slightly higher than those from the swimming sea lion; at all other frequencies, the peak level recordings of the D-tag in one position and on the swimming sea lion were similar (Figure 7). The D-tag on the swimming sea lion recorded flow noise created by the movement of the sea lion, harness, and D-tag through the water, containing energy over the entire measurement frequency bandwidth. However, the flow noise was minimal relative to the SPL of the NBs and, thus, did not affect the recorded SPLs of the NBs (Figure 7b).

SPLs Measured with the Turning D-Tag

Measurements taken from the D-tag turning on its axis at location B4 in the pool without its housing, in its housing, and in its housing and harness on the California sea lion showed frequency-dependent SPL patterns in relation to the angle (Figure 8). Generally, per NB center frequency, the SPL range of the D-tag without its housing was the smallest; the range increased with the addition of the housing, and increased further with the harness attaching the D-tag to the sea lion (Table 4). At many of the NB frequencies, the lowest received SPLs were when the D-tag on the sea lion's body was between 180° (with the sea lion's entire body between the transducers and the D-tag) and 270° (with the left side of the D-tag pointing towards the transducers so that recording hydrophone 1 was facing the transducers, which was contrary to what was expected).


H
H
0°
90°
180°
270°
360°
0.6 kHz (D-tag without housing)
0.6 kHz (D-tag in housing)
0.6 kHz (D-tag on sea lion)
1 kHz (D-tag without housing)
1 kHz (D-tag in housing)
1 kHz (D-tag on sea lion)
2 kHz (D-tag without housing)
2 kHz (D-tag in housing)
2 kHz (D-tag on sea lion)
4 kHz (D-tag without housing)
4 kHz (D-tag in housing)
4 kHz (D-tag on sea lion)
SPL (dB re 1 μPa)
Angle (°)

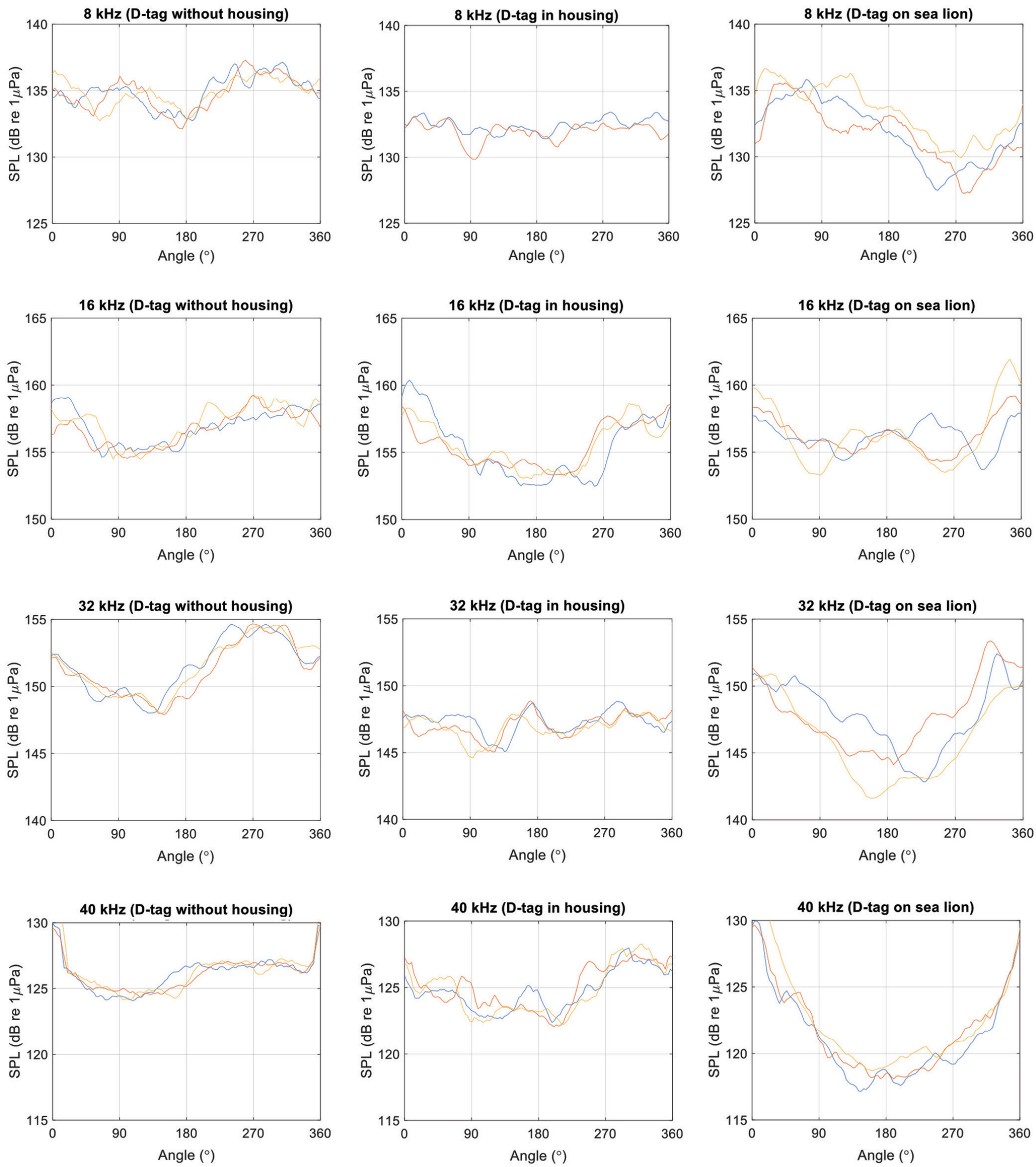


Figure 8. The variation in recorded sound pressure level (SPL) per noise band (NB) center frequency when the D-tag was turning on its length axis in the water column, without its housing (left-hand column), in its housing (middle column), and in its housing and harness, attached to the California sea lion while she rotated on her body axis (right-hand column). The 0° and 360° positions are the same, with the top of the D-tag pointing towards the transducers. The 180° position is with the top of the D-tag facing away from the transducers; when the D-tag was on the sea lion in this position, her body was between the D-tag and the transducers. The 90° position is with the right side of the D-tag pointing towards the transducers so that the hydrophone used for recordings (hydrophone 1) was behind hydrophone 2 (which was not used) and shielded by it. The 270° position is with the left side of the D-tag pointing towards the transducers so that recording hydrophone 1 was facing the transducers. Each color shows one full rotation; $n = 3$ rotations per frequency. The drawings of the turning sea lion (top right) are seen from the position of the transducers. The source level, and thus the recorded SPL, varied with the NB center frequency.

Table 4. Variation in measurements of sound pressure (in three rotations): the range in sound pressure level (SPL) relative to the 0°/360° position with the D-tag turning in the water column with the back of the tag and hydrophones facing the pool's floor, while without its housing, in its housing, and in its housing on the harness, attached to the California sea lion while she turned on her body axis (see also Figure 8). Generally, the recorded SPL range increased when the housing was added and increased further when the harness and sea lion were added. The wavelengths are shown for comparison to the dimensions of the sea lion's body.

NB center frequency (kHz)	~Wavelength (cm)	D-tag only SPL range (dB)	D-tag with housing SPL range (dB)	D-tag on sea lion with housing SPL range (dB)
0.6	250	3	4	9
1	150	3	4	5
2	75	4	6	10
4	38	3	4	10
8	19	5	3	8
16	9	4	7	9
32	5	7	4	9
40	4	6	6	13

Discussion

In the pool, SPLs recorded via the D-tag on a free-swimming California sea lion were ~8 to 10 dB lower than those measured via the grid hydrophones; the differences varied by NB center frequency. This shows that SPLs and spectra measured via the D-tag are influenced by directionality associated with the D-tag itself, the housing, and acoustic effects of the sea lion's body. Measuring mean sound levels in test pools using hydrophones deployed on grids is a valid method. However, depending on research questions, attaching tags to wild marine mammals may be more feasible than using hydrophone grids or arrays at sea.

Evaluation of the Data

The SPLs measured at the 14 grid locations varied per location at each depth and between depths. At the lower NB center frequencies (0.6 and 1 kHz), there were larger differences between the mean SPLs at 0.1 and 1 m depths than at higher frequencies, probably due to the longer wavelengths of the lower frequencies (Table 4). The means of all 28 measurements made with the B&K 8106 hydrophones and of all those made with the D-tags on the grid were within 3 dB of each other, with the D-tag's mean SPLs being generally lower. The lower mean SPL recorded by the D-tag can be explained: the B&K 8106 hydrophones are omnidirectional, but the hydrophones within the D-tag are directional. This directionality, tested in an anechoic basin, is frequency dependent (1.5, 6.5, and 15 kHz were tested); the higher the frequency, the higher the directionality (Wensveen, 2016). In the present study, the D-tag was kept in the same orientation (with hydrophone 1 facing in the same direction) during the measurements. Therefore, during the grid measurements, the D-tag was ensonified at different angles by sound coming from the stationary transducers. However, probably due to the reverberations, the difference in mean SPL between the B&K 8106 hydrophone recordings and the D-Tag recordings was not clearly frequency dependent (Table 1).

The small differences in the mean SPL recorded by the D-tag between the two sessions with the tag on the free-swimming California sea lion for each NB showed good repeatability and confirms that the general swimming patterns in the two sessions with each NB were similar (as was also observed with the video recordings). The low variation (0 to 4 dB) in D-tag SPL measurements between the sessions with the sea lion at the listening station also showed good repeatability when the sea lion was in the same position relative to the sound source. When the orientation towards the transducer was the same, at the same depth, similar received SPLs were measured. The differences were highest for the lower frequencies (0.6 to 4 kHz), probably due to the longer wavelengths than those of the higher frequencies.

When the SLs of the NBs were reduced in two steps of 6 dB, the mean SPLs recorded by the D-tag on the free-swimming California sea lion and the D-tag in its housing in one position showed good linearity except for one attenuation step with the NB at 16 kHz. This phenomenon was measured in both situations, and repeated measurements produced the same results, so this poorer linearity may have been caused by reverberations in the pool or non-linearity in the electronics of the D-tag. Testing with the B&K 8106 hydrophones showed that the sound-producing system was linear at 16 kHz.

Reasons for Differences in SPLs Measured

The mean SPLs determined from hydrophones on a grid were higher than those from the D-tag on the swimming California sea lion, which may partly be due to differences in the hydrophones and partly for reasons evidenced from the other measurements taken. Measurements from the omnidirectional hydrophones on the grid were made under stable conditions with no study animals present and no waves at the water surface; such waves would create reflections and additional noise. The D-tag hydrophone was directional; and when the D-tag in its housing was attached to the harness on the sea lion, the housing and the sea lion's body increased the directionality of the measurements.

The directionality patterns when the California sea lion was rotating on her body axis varied with her position in relation to the transducer and the frequency of the NB; this variation affected the measurements from the D-tag on the free-swimming sea lion by reducing the SPLs, which was not the case with the hydrophone grid measurements. When the D-tag was attached to the sea lion's back, her body blocked the transmission of sounds coming from lateral and ventral positions. Her body reflected the sounds' energy, causing increased shielding at the D-tag location and SPL variation around her body due to diffractive scattering (Wensveen, 2012; Brinkløv et al., 2022; Larsen et al., 2022; see also Wisniewska et al., 2016). Also, when the sea lion surfaced to breathe, the D-tag was briefly raised above the water surface, which slightly reduced the recorded mean SPL. In summary, the directional aspects of sound reception by the D-tag on the sea lion's back, coupled with shielding and surfacing, caused the lower received SPLs recorded by the D-tag relative to the SPLs measured with the stationary omnidirectional hydrophones on the grid. This directionality effect in the D-tag recordings can be compensated for during analysis by selecting the highest SPL in a quickly changing recorded SPL sequence, based on the assumption that SPL is reduced by body shielding (Patrick Miller, pers. comm., 2023).

Suggestions for Future Research

The D-tag was attached to the California sea lion with its front towards the sea lion's head because of the tag's hydrodynamic shape. Thus, the D-tag's back and its hydrophones pointed towards the rear of the sea lion. Placing the D-tag with its hydrophones facing forward would have made little difference to the mean SPL recorded because the sea lion mostly swam clockwise ovals facing both towards the sound-producing transducer and away from it.

Hearing in mammals is directional: the SPL received by the ears depends on the angle at which the sound reaches the ears. The directionality of hearing has been measured in only a few marine mammal species: in bottlenose dolphins (*Tursiops truncatus*; Au & Moore, 1984; Accomando et al., 2020), in a harbor porpoise (*Phocoena phocoena*; Kastelein et al., 2005), and in two harbor seals (*Phoca vitulina*; Kastelein, unpub. data). The directionality of hearing is a result of a mammal's body position relative to the sound source in which the body may attenuate sound (by shielding and absorption) or amplify sound (with internal structures), thus affecting the SPL that reaches the ears. Therefore, even the SPL recorded near the ears of a marine mammal differs from the SPL received by the ears, as the body may attenuate, amplify, and filter sound which eventually reaches the ears. More studies like those conducted by Cranford et al. (2008, 2010) and Cranford & Krysl (2015) are needed to reveal acoustic pathways in other marine mammal species, and to improve understanding of acoustic pathways towards the ears. In future studies, the D-tag should be placed on the head, or as close to the head as possible (i.e., the neck), to mimic more realistically the acoustic shielding effect of the sea lion's body on its ears.

Very high SLs were used in the present study, as the SPLs in the pool were intended to be similar to SPLs of fatiguing sounds used in TTS studies with California sea lions (Kastelein et al., 2021, 2022a, 2022b, 2024, 2025). So, in the present study, the mean recorded SPLs were not affected by the lower SPL flow noise; however, at lower received levels, flow noise could affect the recorded SPLs (e.g., Wisniewska et al., 2016, found that flow noise made by a swimming harbor porpoise limited the measurement of vessel sounds via D-tags). If both D-tag hydrophones are used for recording, some of the flow noise can be removed with acoustic analysis methods (von Benda-Beckmann et al., 2016). Still, flow noise should be considered in D-tag design, and attachment methods could be improved for future studies with expected received levels of target sound closer to flow noise levels.

In sum, future research should be focused on improving D-tag design, including its overall size and shape, housing and attachment devices for wild and captive studies, and hydrophone directionality and placement within the D-tag. The position of D-tags on the body of the study animal is also likely to be important and should be optimized.

Conclusion: Advantages and Disadvantages of Measurements from Hydrophones on Grids and D-Tags on Free-Swimming Marine Mammals

Both methods of estimating the sound exposure of marine mammals (via omnidirectional hydrophones on a grid or via a D-tag on a swimming marine mammal) have advantages and disadvantages (Table 5).

Omnidirectional hydrophones arranged on a grid or array can be used to quantify an SPL distribution; however, if the study area is large, large numbers of measurements in large numbers of locations may be required to assess the SPLs animals may experience, especially if the SPL fluctuates. Attaching a D-tag can be invasive in wild marine mammals, and in captivity, it requires extensive training of subjects. A D-tag attached to a marine mammal, however, records the SPLs encountered in the potentially very large areas that the individual mammal actually occupies. For example, in the present study, the California sea lion generally swam in a clockwise circular pattern during sound exposure sessions and, thus, spent more time in the periphery of the pool than in the center (i.e., she frequented grid locations B2, B3, and B4 much less often than other locations). Measurements from the D-tag on the harness reflected the sea lion's movements more closely than measurements from the hydrophones on the grid. However, the directional reception properties of D-tags are exacerbated by the housing and by body shielding of the sea lion. Also, D-tags can be lifted out of the water during respiration (Table 2), as was observed during the present study. This is an advantage if the goal is to measure what the subject actually experienced. If the ears are out of the water, the animal probably cannot hear the entire spectrum of underwater sound. So, this is part of the D-tag providing information about what the sea lion experienced.

Table 5. Hydrophones on a grid or array or a D-tag on the marine mammal: a summary of the advantages (+) and disadvantages (-) of the two measurement methods used to determine the sound pressure levels (SPLs) that marine mammals are exposed to in a pool, net pen, or at sea. Deployment at sea includes studies in small, defined areas (e.g., in a lagoon or close to a fishing net, fish farm, development, or sound source), and those in which the grid points are not sampled simultaneously but from a vessel moving between the points.

Hydrophones on a grid or array	D-tag on a free-swimming marine mammal
No training or capture required (+)	Attaching the harness and/or tag to the animal requires training, giving chase, or capture (-)
Behavior is not affected (+)	Behavior may be affected by the attachment of the D-tag, especially in wild marine mammals (-)
High-quality, calibrated hydrophones can be used (+)	Less optimal hydrophones are used as they need to be smaller and can be lost if deployed at sea (-)
A large number of measurement locations are needed, especially if the study area is large (-)	• Measurements can be taken easily and frequently as the subject swims freely (+) • In studies of wild mammals, a large sample size (per species/sex/age class) may be needed (-)
Hydrophones can be omnidirectional (+)	So far, D-tag hydrophones have been directional (-)
Not affected by the subject's body (+)	Affected by shielding, refraction, absorption, and reflection by the body and D-tag housing (-)
Even within a pool, only the approximate swimming area is sampled (-). At sea, the measurements cannot be directly related to swimming (-). In a pool or net pen, the swimming area could be assessed more precisely by using video recordings or a tag to measure swimming depth. (+)	Precise swimming area and depth are sampled (+)
Can be used to describe a gradient in SPL (+)	Can show how a subject occupies a gradient (+)
Does not include surfacings and the potential resulting SPL reductions (-)	Includes surfacings and the resulting SPL reductions (+)
May overestimate the mean received SPL due to the exclusion of surfacings and effects of the subject's body (-)	May underestimate the mean received SPL due to directionality of the hydrophones and effects of the subject's body and D-tag housing (-). This could be mitigated in the analysis by excluding low values where surfacings or shielding has taken place.

Other considerations include whether the sounds are to be recorded in a pool, in a net pen (e.g., in a sea bay), or at sea. Measurements at sea may be carried out in small, defined areas (e.g., in a lagoon or bay, or close to a fishing net, fish farm, development, or sound source), and can include grids or arrays in which the grid points are not sampled simultaneously (i.e., they are sampled over time by deploying hydrophones from research vessels moving between the grid points).

Direct association of SPL measurements with hearing tests on trained subjects to estimate noise masking or magnitudes of TTS can only be done in a pool or in a net pen. Pool sides create reverberations that affect the sound field, and the relatively small size of a pool or net pen typically means that the sound source is close to the subject, which may result in an SPL gradient within the testing area, especially in a large pool or net pen. In smaller pools, reflections usually reduce or prevent SPL gradients, resulting in a more homogenous sound field. If a sound gradient needs to be assessed or described, a hydrophone grid or array is the only option, but a D-tag may help to show how a marine mammal uses or occupies such a gradient (Table 5).

In the present study, the mean SPL measurements from the D-tag on the swimming California sea lion were lower than those made with hydrophones on the grid, so measurements from a hydrophone on a grid may be more suitable for quantifying sound exposure of marine mammals in studies of TTS in pools than measurements with D-tags. However, both methods are valid, and attaching tags to wild marine mammals may be more feasible than using hydrophone grids or arrays at sea. For field studies, the development of D-tags has been beneficial. Future technological developments in sound recording tags may overcome some of the issues described herein; methods for hydrophone deployment at sea may also develop. In the meantime, researchers should select the most appropriate method for their experimental design (see information in Table 5).

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