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The characterisation of underwater noise at facilities holding marine mammals

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Abstract

*A collaborative effort was undertaken to delineate underwater noise levels within holding enclosures at marine mammal facilities. Ambient noise levels were measured under normal operating conditions in the enclosures of 14 participating facilities. Facility habitats varied from ocean environments to fully enclosed pools. The means and standard errors of the noise pressure spectral densities measured across all pools were similar to those measured in natural coastal environments with relatively low presence of anthropogenic noise. Highest levels of noise in land-based pools were generally at frequencies < 2 kHz and primarily due to the operation of water treatment/filtration systems. Noise levels in land-based pools were comparable to or lower than semi-natural and natural systems at higher frequencies because of the presence of biological noise sources in these systems (eg snapping shrimp [*Alpheus *spp]). For odontocete enclosures, the whales themselves were often the greatest source of sound at frequencies where the whales have their best hearing (~40–100 kHz). The potential for facility ambient noise to acoustically mask odontocete communication signals and echolocation clicks appears to be low. In general, when noise was elevated it was at frequencies outside the typical frequency ranges of whistles and echolocation clicks, and where odontocetes have poor hearing sensitivity. Occasional noise issues were found; it is therefore recommended that facilities periodically assess enclosure noise conditions to optimise animal management and welfare.*

Keywords: *animal enclosures, animal welfare, bottlenose dolphin, California sea lion, marine mammals, noise*

Introduction

The majority of marine mammals held at marine mammal display facilities include bottlenose dolphins (*Tursiops truncatus*) and sea lions (*Zalophus californianus* or *Otaria flavescens*). To a lesser extent, killer whales (*Orcinus orca*), belugas (*Delphinapterus leucas*), pilot whales (*Globicephala* spp), Commerson's dolphins (*Cephalorhynchus commersonii*), harbour seals (*Phoca vitulina*), and sea otters (*Enhydra leutris*) are also held, along with a few other exotic species. Many of these marine mammals have excellent hearing sensitivity underwater and exhibit a greater frequency range of hearing than humans (eg Johnson 1967; Reichmuth *et al* 2013). Relatively little in the way of characterising the underwater acoustic environments of marine mammals under human care has been performed, yet these environments are potentially exposed to sounds that are inaudible in air (eg coupled through the enclosure walls) and inaudible to human caregivers (ie above the frequency range of human hearing but audible to many marine mammals). A lack of information on ambient noise within marine mammal facilities has led to speculation about the quality of the acoustic environments and the potential for sound to negatively impact marine mammals at these facilities. For example, some have speculated that marine mammal enclosures may be subject to high levels of noise from life support systems (LSS; eg water filtration and treatment) and other facility operations (Williamson *et al* 2011). Conversely, others have suggested that marine mammal facilities provide environments that are acoustically sterile and that animal acoustic behaviour becomes abnormal as a result (eg reductions in the production and amplitude of echolocation signals by odontocetes, such as dolphins and belugas; Rose *et al* 2009). The experience of chronic stress due to these opposing acoustic conditions has also been hypothesised (Williamson *et al* 2011).

Little comprehensive reporting on the acoustics of marine mammal facilities exists. Scheifele and colleagues (2012a,b) recorded noise levels at the Georgia Aquarium in order to characterise the impact of LSS operations and in-air sound (eg music and sound effects) on underwater noise levels within the dolphin and beluga exhibits. They concluded that LSS operations contributed mostly to frequencies below 1,000 Hz, where dolphin hearing is relatively insensitive, and that the playback of soundtracks did

Table 1 Participant facilities and facility location.

Facility	Location
Aquatica	Orlando, FL, USA
Brookfield Zoo	Brookfield, IL, USA
Dolphin Connection	Duck Key, FL, USA
Discovery Cove	Orlando, FL, USA
Dolphin Quest	Bermuda
Georgia Aquarium	Atlanta, GA, USA
Marineland	St Augustine, FL, USA
Miami Seaquarium	Miami, FL, USA
Mirage	Las Vegas, NV, USA
National Aquarium	Baltimore, MD, USA
Resorts World Sentosa	Singapore
SeaWorld	Orlando, FL, USA
Shedd Aquarium	Chicago, IL, USA
Theater of the Sea	Islamorada, FL, USA

not significantly increase underwater noise levels in the habitat even when transmitted at aerial, weighted sound pressure levels (SPLs) of 100 dBA (A-weighted sound level in dB re 20 μPa). Outside of the work of Scheifele and colleagues (2012a,b), little peer-reviewed information on underwater ambient noise at aquaria and marine mammal facilities exists (although work specific to acoustics in dolphin welfare is emerging; Spence 2015).

In an effort to better understand the acoustic environment of the marine mammals under their care, a group of marine mammal facilities participated in a survey of the underwater acoustic environment of marine mammal enclosures. The study presented here reports the outcome of this investigation. Marine mammal facilities with varying habitat structures, from natural habitats to fully enclosed pools, agreed to have ambient noise levels measured within their pools and enclosures. Additional measurements were made in ocean habitats inhabited by marine mammals, specifically bottlenose dolphins and California sea lions. The objective of the survey was to determine average ambient noise levels within marine mammal pools from a cross-section of facilities, to assess the acoustic variability of the same, and to characterise the ambient noise relative to acoustic conditions in natural environments with and without substantial anthropogenic activity. This study provides baseline information on the ambient noise of habitats in which marine mammals under human care are housed and provides a foundation upon which habitat noise management can be based.

Materials and methods

Facilities

This study was carried out over a four-year period and involved fourteen different marine mammal facilities. Recording systems were deployed at the facility pools for the purposes of ambient noise characterisation and with the goal of capturing noise produced during typical operating conditions of the pools (ie pumps and filtration systems running). Over the course of time, enclosures will experience noise events associated with cleaning, other maintenance, construction, etc. The goal of this effort was not to capture the variability in noise exposure that might occur over a long period of time associated with these types of events, and which are sporadic or intermittent in occurrence, but to characterise the noise exposure experienced by the animals during the greatest portion of their noise exposure history. For purposes of characterising the ambient noise of the enclosures, noise associated with animal vocalisations or the operation of infrequent noise sources (eg mechanical gates) was intentionally excluded from the analysis. Although the goal of this effort was to characterise ambient noise conditions of marine mammal pools and enclosures within and across both pools and facilities, issues associated with any specific pool, though reported here without attribution to a particular facility, were reported to the responsible facility for further action. The contributing facilities and their locations are provided in Table 1. Specific species kept in the enclosures that were characterised, included bottlenose dolphins, killer whales, belugas, Commerson's dolphins, Pacific white-sided dolphins (*Lagenorhyncus obliquedens*), and California sea lions.

Seventy-seven pools and animal enclosures were assessed. The enclosures ranged from fully enclosed, land-based pools with hard or soft bottoms and closed filtration systems, to soft-bottom enclosures with natural water influx, to open-netted enclosures in the natural environment. Hereafter, these are referred to as 'pools', 'semi-open enclosures', and 'open-water enclosures', respectively.

Pools of similar type were grouped for analysis using the classification scheme of Couquiad (2005). Pool groupings consisted of main pools, holding pools, and medical pools. The main pools were generally the largest pools and commonly used for animal viewing, although long-term animal holding also occurred. Holding pools, which made up the majority of the number of pools, were generally smaller than main pools and used for temporary housing, animal separations, training, and husbandry routines. Medical pools were pools specifically designed for veterinary procedures. The maternity pool was an additional pool type occasionally encountered at facilities, but these did not differ substantially from holding pools or main pools, depending on size, and are therefore classified as either holding pools or main pools for the purpose of analysis.

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Animals within open-water enclosures experience all of the physical (eg tidal changes, salinity, water temperature) and biological (eg fish and snapping shrimp [*Alpheus* spp]) attributes of the natural site where the enclosure is located, as well as daily and seasonal variation in those attributes. Semi-open enclosures were characterised as large habitats that may or may not be compartmentalised by gates; however, even when compartmentalised, water freely flowed between compartments. Semi-open enclosures were supplied by seawater with little to no filtration but were not in direct contact with the ocean. Because of the natural seawater supply, the semi-open enclosures contained biological sources of noise typical of the ocean (eg snapping shrimp), but to a lesser degree than open-water enclosures.

Comparison sites

Noise measurements were made at several natural locations for comparison to the measurements made in the marine mammal enclosures. Sites were selected to include deep and shallow water environments, as well as environments with heavy anthropogenic activity and environments with relatively little human activity. Noise measurements were made within San Diego Bay to represent a shallow water environment influenced by anthropogenic activity. Measurements were made off of the Florida Keys to represent shallower water environments less affected by anthropogenic activity, but which are similar to environments commonly encountered by coastal-dwelling dolphins. One measurement was made approximately 1 mile east of Duck Key, FL over a sandy ocean bottom. A second measurement was made approximately 4 miles east of Duck Key, FL over a reef system. The second measurement was performed to determine potential differences in ambient noise due to the greater presence of biological noise sources on the reef. A final measurement was made approximately 10 miles west of San Diego, CA in water depths > 1,000 feet. This deep-water measurement was made in order to characterise the noise of natural environments where the presence of biological noise sources is relatively low.

Measurements

Measurements were made in a manner that provided a cross-sectional sample of the ambient noise of a broad number and type of enclosures used to house marine mammals (ie short-duration measurements made across many enclosures; long-duration measurements within individual enclosures were not made). The design was implemented to characterise the typical ambient noise of each enclosure; no intentional effort was made to determine or characterise the maximum level of sound due to acoustic events that are likely sporadic or intermittent in nature and which do not contribute significantly to the average noise exposure of the animals. Underwater noise was measured with either a TC 4032 low-noise hydrophone (sensitivity = –170dB re 1V μPa^{-1}; Teledyne Reson, Slangerup, Denmark) or a B&K 8105 (sensitivity = –205 dB re 1V μPa^{-1}; Brüel and Kjær, Nærum, Denmark). The hydrophone was placed at a depth of 1 m unless the pool depth was less than 2 m, in which case it was placed at the midpoint of the water column. The hydrophone was always placed a minimum of 1 m from pool walls or from walkways, if within a netted enclosure. Recordings were high-pass filtered at 10 or 20 Hz and amplified with 20–32 dB of gain using a Reson VP1000 voltage pre-amplifier. Noise samples were collected using a rugged notebook computer with a PCI expansion chassis containing a multifunction data acquisition board (PCI-6251; National Instruments, Austin, TX, USA). Noise was digitised with 16-bit resolution and at a sampling rate of 500 kS s^{-1}, which provided a frequency bandwidth (250 kHz) that exceeded the hearing bandwidth of marine mammals. Each measurement was saved as a .wav file. Each noise recording was typically 15 s in duration, which is the minimum duration recommended for the recording of indoor noise due to machinery (eg LSS; American National Standards Institute [ANSI]/Acoustical Society of America [ASA] S12.72 2015). Occasionally, longer samples were collected, and multiple recordings were made at each location in order to obtain an average estimate of noise within the pool or enclosure. Every effort was made to make noise recordings in the absence of marine mammals. To this end, animals were either relocated to other enclosures or held with their heads out of the water by animal care staff during the recordings to minimise interference from marine mammal vocalisation; however, this was not always feasible and some recordings had to be made with animals present in the pools/enclosures.

Analysis

The noise pressure spectral density (PSD; which is analogous to acoustic intensity in 1 Hz increments; dB re 1 $\mu Pa^2 Hz^{-1}$), and noise SPL in 1/3-octave frequency bands (OTO; dB re 1 μPa) was determined for each marine mammal enclosure or comparison site by averaging sequential 50-ms segments (typically, n = 300, total duration 15 s) within a noise recording. Segments of 50 ms were deemed suitable enough to provide sufficient samples for detailed frequency analysis (25,000 samples in the window) but short enough to prevent transient events from strongly biasing the resulting average. The PSD was calculated using an 8,192-point fast Fourier transform (FFT) with a Hanning window (no overlap). In order to diminish spectral peaks due to radio frequency interference at high frequencies, which was observed at some facilities, a median smoothing function was performed above 5 kHz using a 20-point sliding window when visualising noise levels.

For marine mammal enclosures, the mean ambient noise was determined by averaging the PSD and 1/3-octave band noise levels for multiple sites and recordings within the pool or enclosure. (Note that the number of recording sites varied across enclosures and was dictated by enclosure size). Averaging was performed in dB, as opposed to pressure, as the underlying concern for making the measurement was the perception of sound and the ear processes sound pressure in a logarithmic fashion. Subsequently, a mean-of-means was determined for each pool type (ie main, holding, medical) or habitat (ie semi-open enclosures, open-water enclosures) by averaging the mean noise measurements of all individual pools of a given type. Throughout the remainder of the paper, this will be referred to as the 'grand mean,' and the grand mean noise PSD and OTO will be notated as PSD_{gm} and

OTO_{gm}. For oceanic comparison sites, all measurements were made from a single location so averaging only included repeated measurements from the same location.

The standard error of the grand mean was calculated to demonstrate the variability in noise levels across pools. In addition, the maximum and minimum noise PSD or 1/3-octave band was determined from the mean values of individual pools across all pools of a specific type. The purpose of determining the maximum and minimum value in this manner was to demonstrate the worst- and best-case scenario for a particular PSD frequency bin or 1/3-octave band. It is important to note that the plots resulting from the maximum and minimum values do not correspond to a particular pool; rather, they are specific to a frequency bin or 1/3-octave band as measured across all pools and enclosures.

All files were screened for the presence of marine mammal vocalisations and files selected for analysis were based on the absence of vocalisations or a minimum amount of interference due to their presence. Select files with marine mammal vocalisations were analysed for comparison to conditions when marine mammals were absent. Similarly, several sound-producing events associated with facility operations were recorded and analysed (eg gate operations). Recordings were of the same duration as previously noted and were analysed in the same manner, although there was generally only one recording per sound-producing event.

Although sampled at 500 kS s^{-1}, noise measurements off the Florida Keys were only reported for frequencies below 170 kHz due to the presence of an active depth sounder on the boat used to travel to the recording location. Noise measurements made in deep water were full bandwidth.

Results

The PSD_{gm} and OTO_{gm} measurements for the different pool types (ie main, holding, and medical) are presented in Figures 1 and 2. Each figure also provides the standard error of the PSD_{gm} or OTO_{gm} for all pools of a given type, as well as the maximum and minimum value for each PSD bin and 1/3-octave band measured across all pools. The PSD_{gm} was generally similar across the pool types, with a highest grand mean value of 90–100 dB re 1 μPa^2 Hz^{-1} at the lowest frequencies measured and declining with increasing frequency to less than 50 dB re 1 μPa^2 Hz^{-1} above 100 kHz. The standard error of the mean was generally less than 10 dB across all pool types. The maximum PSD level measured in any pool, in the absence of both animal noise and infrequent facility activities (eg gate operations or construction), was ~130 dB re 1 μPa^2 Hz^{-1} and occurred below 100 Hz. In general, the highest PSD levels measured occurred at frequencies less than 1 kHz. Maximum and minimum PSD levels could be as much as 43 dB above and 28 dB below the grand mean, respectively, although a true minimum could not be detected in many cases (particularly at higher frequencies) because the measured SPL was at the limit of self-noise for the recording equipment. A notable spectral peak at 11.7 kHz is apparent in the maximum PSD of the main holding pools (Figure 1[a]). This peak was due to measurements within a single pool and determined to be associated with electronic equipment co-located with the pool. The signal was not artifactual (ie it was an acoustic signal that was clearly audible) but was only found to occur in this one pool.

The OTO_{gm} was also greatest below 1 kHz across all pool types (Figure 2), generally declined with increasing frequency, but levelled off (or slightly increased) above 30 kHz. As with the PSD_{gm}, the standard error of the OTO_{gm} was generally ~10 dB. Maximum and minimum 1/3-octave levels were as much as 41 dB above and 28 dB below the grand mean, respectively. However, as noted above, the true minimum is likely lower than reported due to self-noise limitations of the recording equipment.

The PSD_{gm} in the semi-open enclosures (Figure 3) was greatest below several hundred Hz. However, unlike the enclosed pools, noise levelled off or increased between 1–10 kHz. At the lowest frequency reported (100 Hz), the PSD_{gm} and OTO_{gm} were ~20 dB below those of the enclosed pools. At frequencies in the tens of kHz, noise levels within the semi-open enclosures were marginally higher than that observed in the enclosed pools. The increase in noise at these frequencies was from the presence of biological noise sources (excluding the animals themselves), predominantly snapping shrimp. (Note that the standard error of the means for the PSD_{gm} and OTO_{gm} were greater than the maximum/minimum deviations from the grand mean; this result is a statistical outcome of the small sample size representing semi-open enclosures).

Only a single open-water enclosure was tested during the survey (Figure 4). The mean PSD of the open-water enclosure was similar to the PSD_{gm} measured in the semi-open enclosures, although levels ranged from 6–10 dB higher in the 1–100 kHz frequency band. At the highest measured OTO, levels were ~10–12 dB above the grand mean level measured in the semi-open enclosures but were very similar to levels one standard error above the grand mean. The increase in noise within the compared frequency bands correlated with a greater presence of snapping shrimp in the natural environment.

For both the semi-open enclosures and the open-water enclosure, PSD_{gm} below 1 kHz was ~20–30 dB lower than the comparable PSD_{gm} of the pools. Above 10 kHz, the PSD_{gm} and 1/3-octave band noise levels of enclosed pools were similar to or lower than the open-water enclosures and semi-open enclosures. However, the highest-level scenario for noise (PSD and 1/3-octave) at any specific frequency was always found to exist within the enclosed pools.

Transient sources of mechanical noise in the facilities ranged widely in the level of noise produced. For example, Figure 5 compares the noise generated by a mechanical/motor-operated gate (measured ~1 m from the gate) and a mobile medical platform (measured ~1 m over the platform) to the PSD_{gm} (± 1 SEM) of the main pools. During operation, the mechanical gate produced noise at levels as much as 35 dB above that observed for the main

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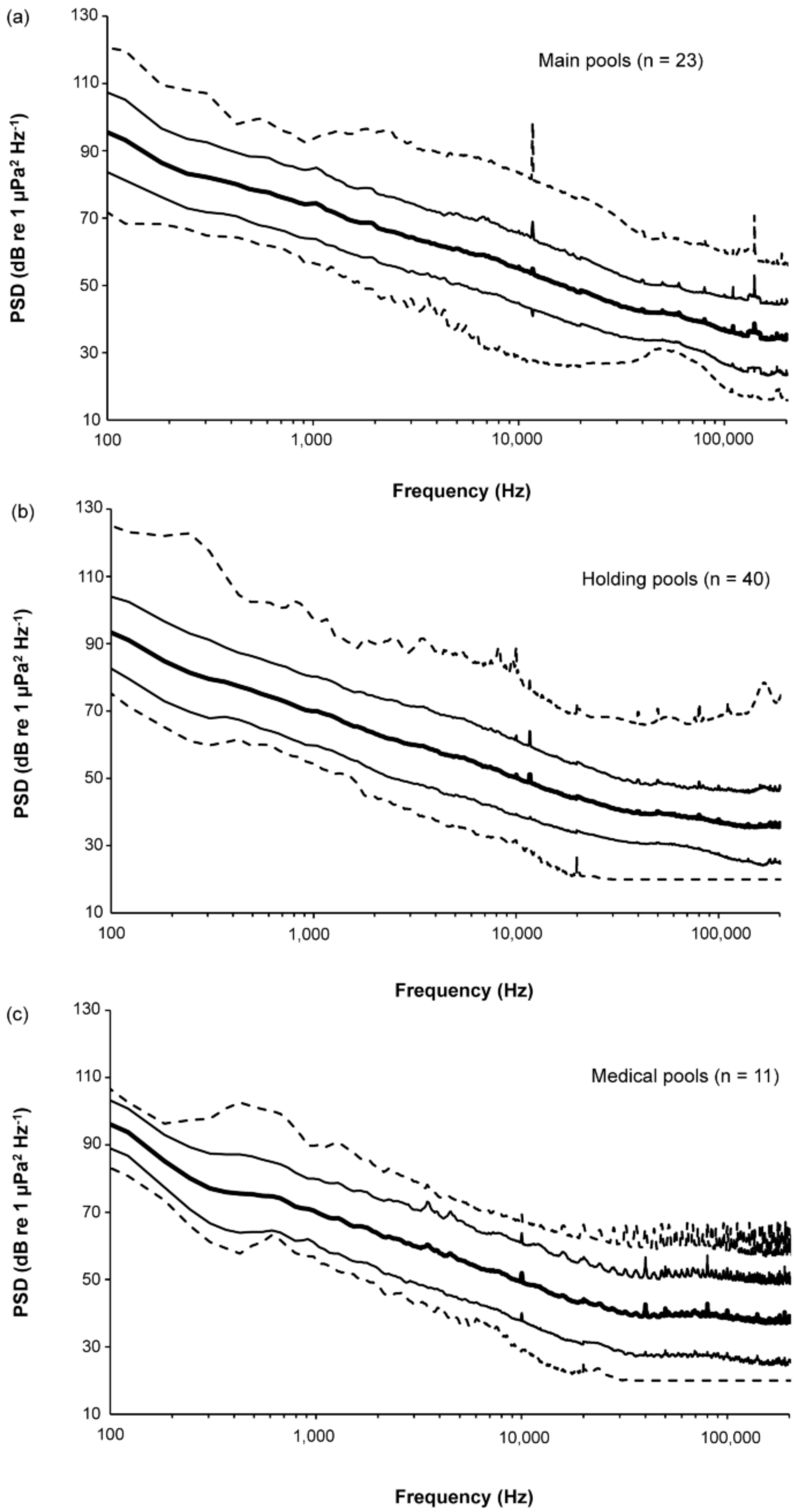
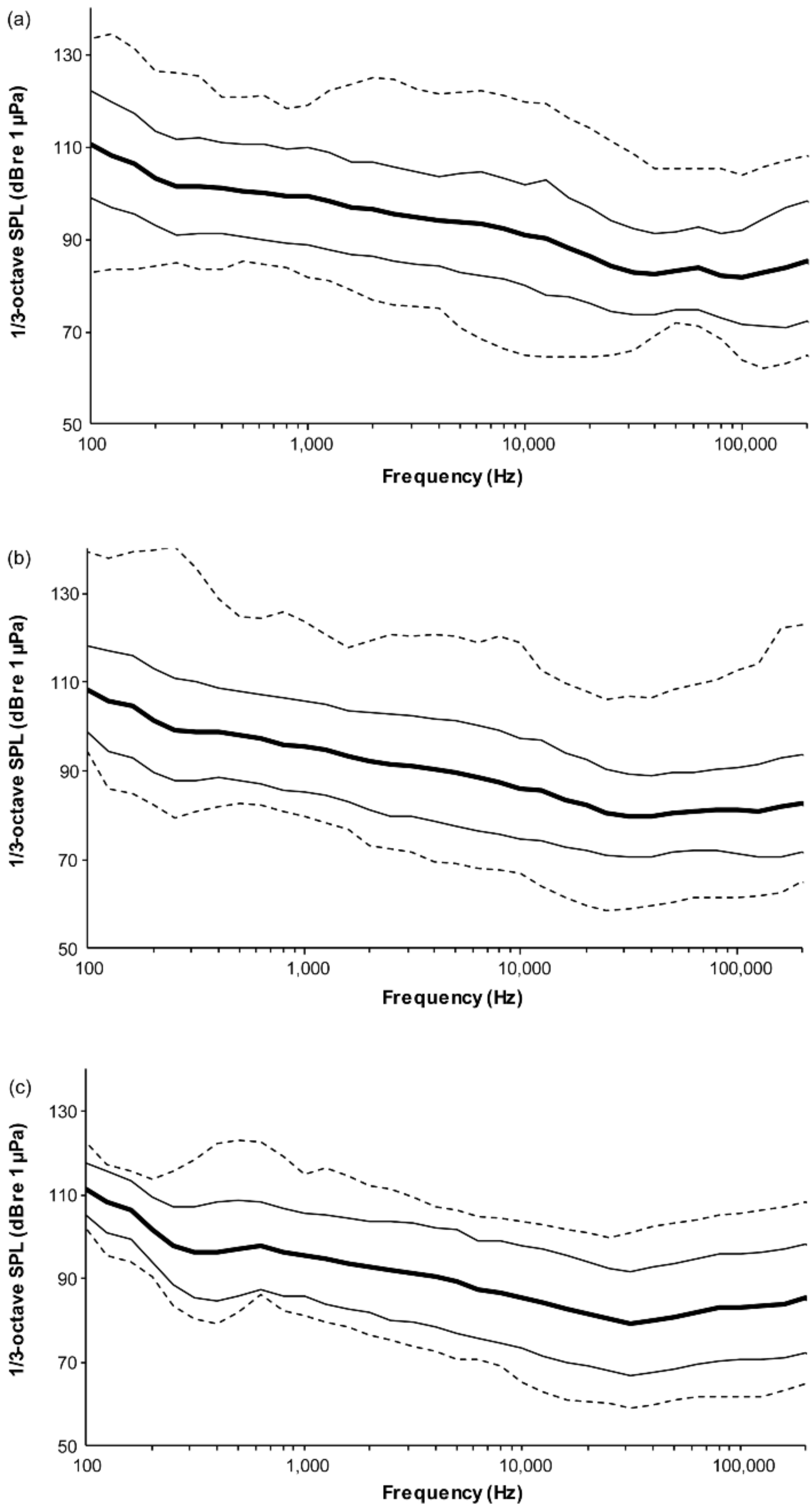
Figure 1



Noise PSD of the various pool types ([a] main, [b] holding and [c] medical pools). The PSD_{gm} (thick solid line), (±) standard error of the PSD_{gm} (thin solid lines), and the maximum and minimum PSD value within each PSD bin as measured across all pools (dashed lines) are provided.

Figure 2



OTO noise levels of the various pool types ([a] main, [b] holding and [c] medical pools). The OTO_{gm} (thick solid line), (±) standard error of the OTO_{gm} (thin solid lines), and the maximum and minimum OTO within each 1/3-octave band as measured across all pools (dashed lines) are provided. Sample sizes are as listed in Figure 1.

Figure 3

Noise PSD and OTO for semi-open enclosures. (a) The PSD_{gm} (thick solid line), (±) standard error of the PSD_{gm} (thin solid lines), and the maximum and minimum PSD value within each PSD bin as measured across all pools (dashed lines) are provided. (b) The OTO_{gm} (thick solid line), (±) standard error of the OTO_{gm} (thin solid lines), and the maximum and minimum OTO within each 1/3-octave band as measured across all pools (dashed lines) are provided. Note that in both panels the standard errors for the PSD_{gm} and OTO_{gm} were greater than the maximum/minimum deviations from the grand mean; this result is a statistical outcome of the small sample size representing semi-open enclosures.

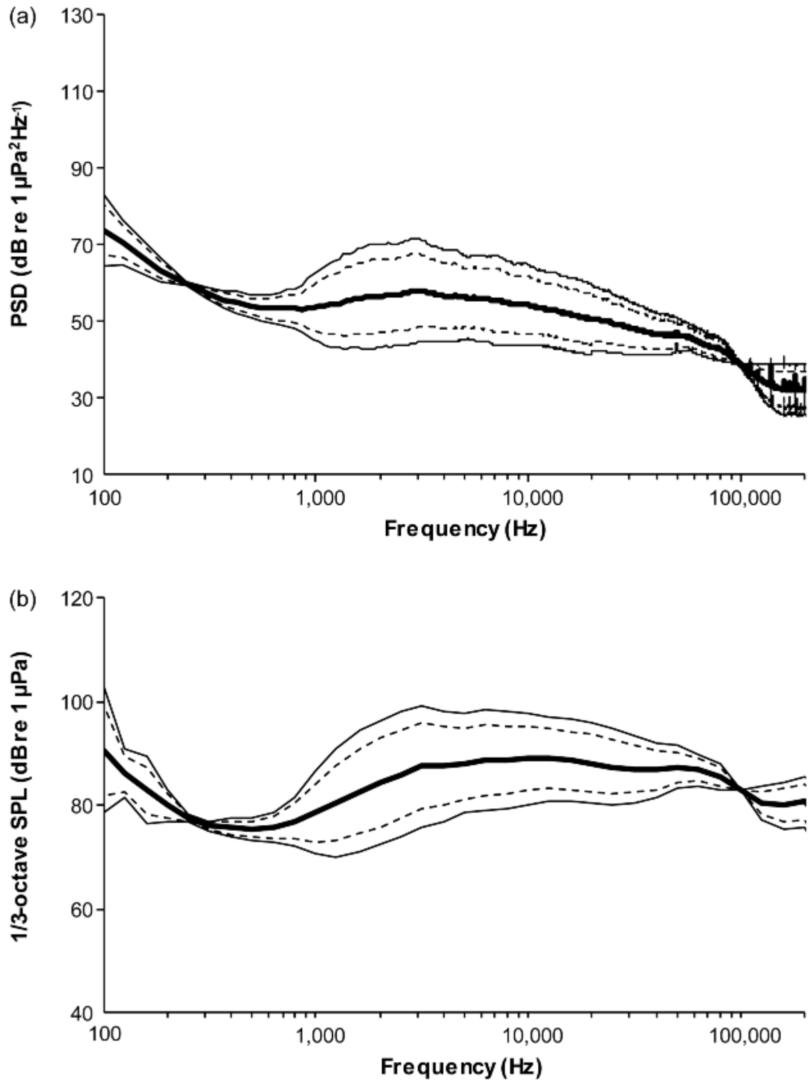


Figure 4

Mean noise PSD (solid line) and 1/3-octave SPL (dashed line) for the open-water facility.

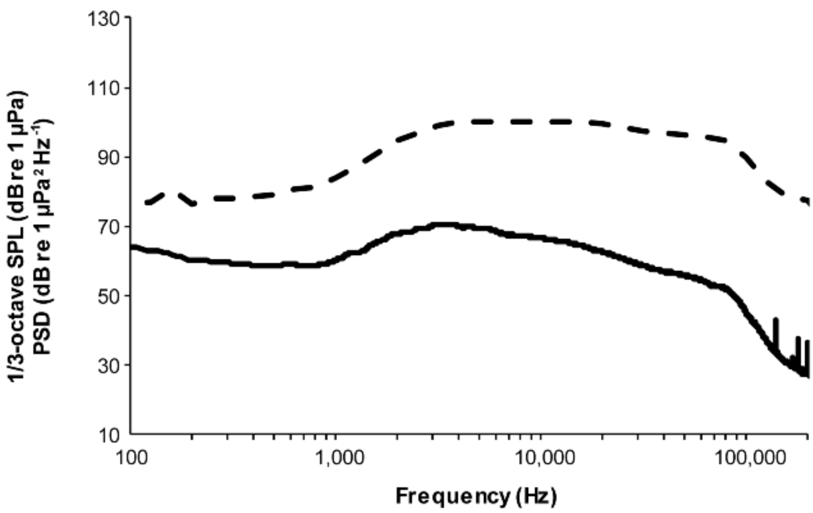
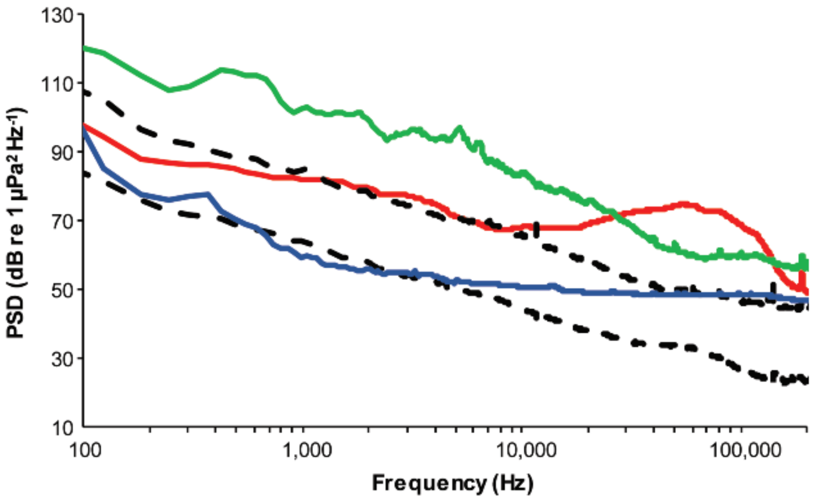


Figure 5



Comparison of the noise PSD of a mechanical underwater gate during operation (green line), a medical platform during operation (blue line), and sounds produced by echolocating and vocalising dolphins within an enclosure (red line). For comparison purposes, (±) standard error of the main pools' PSD_{gm} is provided (dashed lines).

pools' PSD_{gm}. In contrast, the raising of the medical platform resulted in a PSD marginally higher than that of the main pools' PSD_{gm} at frequencies above 20 kHz. The operation of the medical platform negligibly increased noise above the baseline (no platform operation) measured in the same pool and was difficult to audibly identify. The examples provide the extremes of observed mechanical device operations; overall, the noise contribution of transiently operated mechanical devices appeared to be highly variable and device dependent. The duration that devices were operated was also highly variable ranging from a few to tens of seconds.

Odontocetes, if present in the pools, made significant contributions to the ambient noise, particularly between 20–100 kHz (red line; Figure 5). The increase in the 20–100 kHz noise band was due predominantly to the production of echolocation clicks, although odontocetes also produced whistles at lower frequencies. On average, the presence of echolocating animals raised the noise floor by as much as 25 dB, but the amount was variable depending upon recording conditions (eg number of animals, location relative to animals). It was not feasible to track the location of all of the animals in pools where echolocation was recorded, or to determine if echolocating animals were oriented toward the hydrophone (which would increase noise measures at the higher frequencies). Nevertheless, from a qualitative perspective, the presence of animals within an enclosure resulted in a significant contribution to noise levels because of the sounds the animals themselves produced.

The mean noise PSD and OTO levels for several natural environments are presented for comparison to the facility noise measurements in Figure 6(a). Noise levels varied considerably depending on whether measurements were made near shore or in deep water, or in heavily trafficked areas. At frequencies up to 100 kHz, the highest noise PSD was observed in San Diego Bay, although levels measured over the Florida Keys reef were comparable. Noise PSD of the shallow water, sandy bottom location (Florida Keys [coastal]) was similar to that recorded over the reef below 1 kHz but was up to 14 dB lower at frequencies > 1 kHz. As with differences between land-based pools and semi-open/open-water enclosures, the apparent difference in noise between the two locations at frequencies > 1 kHz was due to a greater presence of biological noise sources on the reef. Noise levels were dramatically reduced in deep water away from major influences of anthropogenic and biological noise sources and approached the self-noise of the recording system at the highest frequencies. At frequencies above 10 kHz, the noise PSD could be as much as 30 dB lower than that measured at the coastal, shallow water site.

Figure 6(b) compares the mean noise PSD of the coastal, sandy bottom habitat with the PSD_{gm} of the main pools. The mean noise PSD of the coastal, sandy bottom habitat was most similar to that of all of the pools. Differences between the noise PSD of the two were greatest at 100 Hz, where the PSD_{gm} of the main pools was ~13 dB higher than that of the coastal, sandy bottom habitat. Between 8–80 kHz, the PSD_{gm} of the pools was marginally lower than that of the natural habitats, although differences were generally within 6 dB of one another from 300 Hz–15 kHz. Above 100 kHz, the noise PSD of both the coastal, sandy bottom habitat and the main pools was low (< 40 dB re 1 µPa^2 Hz^{-1}). The noise PSD of semi-open enclosures and open-water enclosures was lower than or comparable to the noise PSD measured in coastal, sandy bottom and reef habitats off the Florida Keys (Figure 6[c]). The natural habitats had relatively minor influences of anthropogenic noise. Semi-open enclosures and open-water facilities were similar, with the exception that the latter experienced a greater presence of biological noise.

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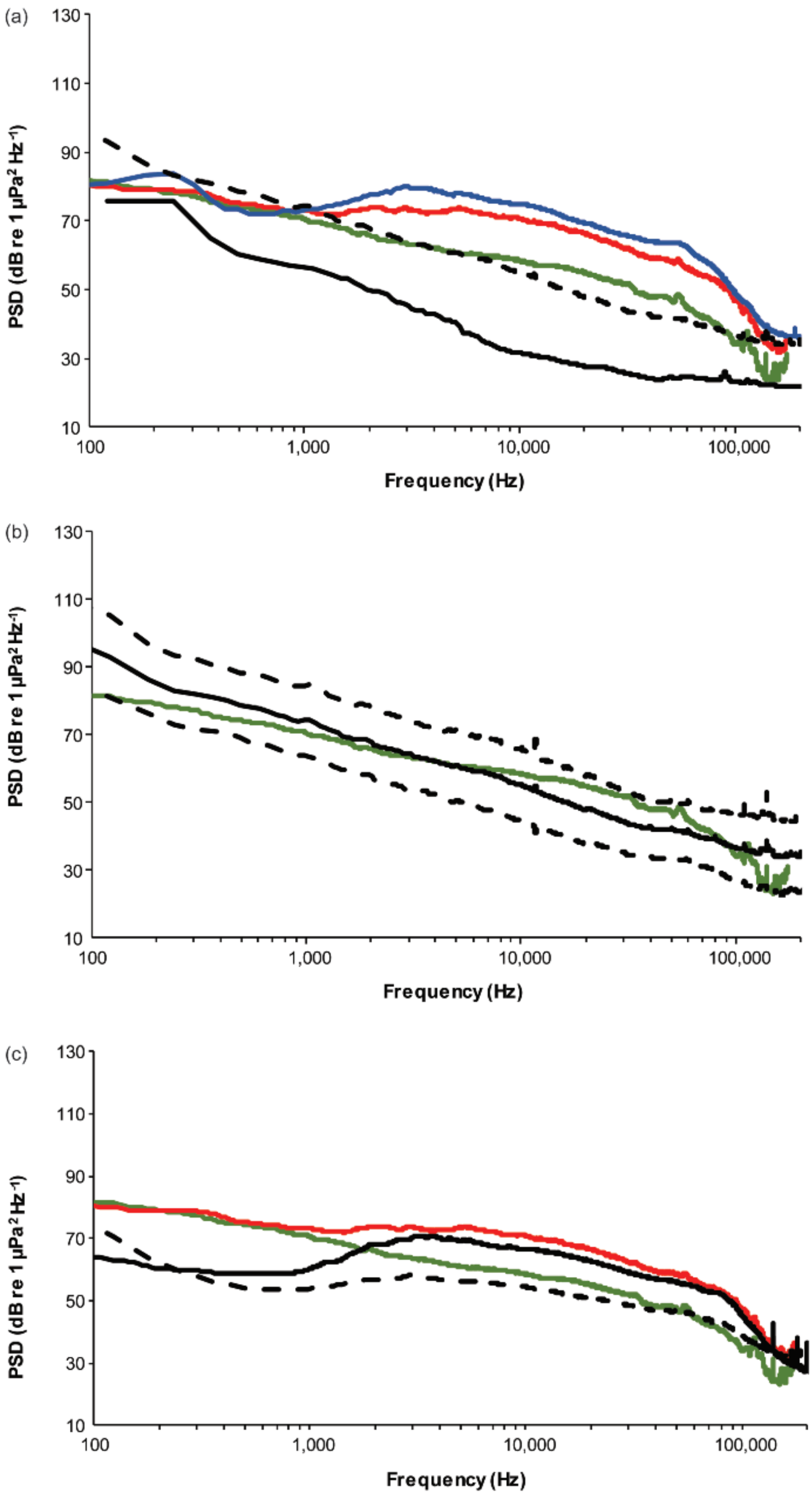
Figure 6



(a) Mean noise PSD obtained from several natural environments: San Diego Bay (blue line); over a shallow, reef system off of Duck Key, FL (red line); over a shallow, sandy bottom off of Duck Key, FL (green line); and in over 1,000 ft of water west of San Diego (black line). The PSD_{gm} for the main holding pools is provided for comparison (dashed line). (b) Comparison of the PSD_{gm} (± SEM) of the main pools to the PSD of water near the Florida Keys (sandy bottom; green line). (c) Comparison of the PSD_{gm} for the semi-open enclosure (dashed line) and open-water enclosure (solid black line) to the PSD near the Florida Keys over a sandy bottom (green line) and reef system (red line).

Discussion

The survey presented here provides the first comprehensive assessment of ambient underwater noise conditions in enclosures holding marine mammals. Across land-based, open-water, and semi-open enclosures, the information should be useful in addressing questions about the overall acoustic conditions within which marine mammals under human care live. Comparisons to natural habitats provide a reference point to which qualitative conclusions about the ambient noise conditions of marine mammal enclosures can be made. It should be noted that the sampling scheme used for this study was cross-sectional in nature, composed of many short-duration noise measurements, often across multiple locations within a pool, and encompassing 77 pools and fourteen marine mammal holding facilities. The goal of the study was to characterise typical noise conditions of the enclosures and provide a statistical assessment of noise exposure conditions across facilities, not to characterise the variability of noise exposure over an extended period of time (eg a year). Sporadic or intermittent noise-producing events will occur at facilities holding marine mammals. Enclosure maintenance, construction, the operation of platforms and gates, etc, provide opportunity for higher level noise events to occur. These events will typically add little to the long-term average noise exposure but can still be cause for concern with respect to auditory fatigue, stress, and behavioural disruption. As noted below, characterisation of such events at any particular facility will necessitate longer duration monitoring schemes than were employed here.

Noise levels were similar across land-based pool types, suggesting no systematic difference between main, holding and medical pools. Pools had higher levels of low-frequency noise (< 2 kHz) than did semi-open enclosures, open-water enclosures, and most natural coastal sites, although the maximum difference in noise PSD was ~30 dB across all comparisons. Higher levels of low-frequency noise were most likely because of the coupling of mechanical sound sources through facility structures and into the pools. Noise from life-support systems (LSS; filtration, ozone treatment, etc), water intakes/outflows, piping, etc can all contribute to low-frequency noise within enclosures. However, most of the facilities with pools had undertaken efforts to minimise low-frequency noise by placing LSS on vibration pads or implementing other noise and vibration mitigation technologies or strategies (eg spatial separation of LSS from pools). Low-frequency noise mitigation designs should continue to be implemented as 'best practice' for marine mammal enclosures, as previously proposed, and in accordance with general considerations for the potential impacts of noise and vibration on terrestrial mammals within various types of animal-holding facilities (Couquiaud 2005; Garber *et al* 2011).

Compared to nearshore natural environments, land-based pools generally had comparable or lower noise levels at frequencies > 2 kHz, although they were higher than measured in the deep-water, offshore location. Within the frequency range considered to be where dolphins (and most small odontocetes) are most sensitive, the greatest elevations in noise occurred when the odontocetes themselves were present and producing sounds (eg whistles and echolocation clicks; Figure 5). Indeed, within moderate to large odontocete social groups, the enclosures could be quite noisy due to animal sound production. Anecdotally, as the size of social groups decreased, the incidence of echolocation/social sounds also decreased. A direct relationship between vocal activity and group size has been observed in wild dolphins (Jones & Sayigh 2002; Cook *et al* 2004), and increases in whistle production have also been observed during dolphin interactions with human trainers (Marulanda *et al* 2016). Conversely, observations in belugas suggest that changes in environment (addition of new species, transportation to new enclosures) correlate with reduced vocal activity and potentially indicate a behavioural response to stress or uncertainty (Castellote & Fossa 2006). Given the sensitive nature of odontocete sound emission to changes in social structure and environment, vocal activity appears to be a potential behavioural index of animal welfare deserving of continued research (Castellote & Fossa 2006).

Semi-open enclosures and open-water enclosures showed generally similar noise characteristics to that of the nearshore environment (sandy bottom and reef) but with levels of noise below 2 kHz lower than observed in land-based pools. The decrease in low-frequency noise is due to a number of possible factors, including: the existence of the facility in very shallow water (which potentially interferes with low-frequency sound propagation), barriers between the facilities and the ocean that attenuate waterborne low-frequency sound, a lack of associated mechanical systems, a lack of hydrodynamic flow from filtration systems, and/or location of mechanical/filtration systems away from the enclosure. Above 2 kHz, the noise of the open-water enclosures was very similar to that of the shallow-water reef system. As the physical structure of reefs attracts organisms, it seems probable that a greater accumulation of biological noise sources occurs on structures associated with the open-water enclosures (eg nets, pilings). In contrast, the semi-open enclosures, which are separate from the ocean, but which utilise ocean water that permits some organisms to pass into the enclosure, were more similar to that of the nearshore, sandy bottom environment. The relatively quieter profile of the semi-open enclosures likely once again relates to the density of biological noise sources within the enclosures and sandy bottom environment. In either case, the biological noise within the semi-open enclosures and open-water enclosures is similar to or the same as that experienced by marine mammals in near-shore environments. Whether the presence of higher levels of 'biological noise,' which in many cases is dominated by snapping shrimp, has an effect on the welfare of the animals in the enclosures is speculative.

Assuming that the effective auditory filter bandwidth of marine mammals is approximately a 1/3-octave in width (eg Southall *et al* 2003), a comparison of odontocete and otariid hearing sensitivity to facility noise levels can be made. For

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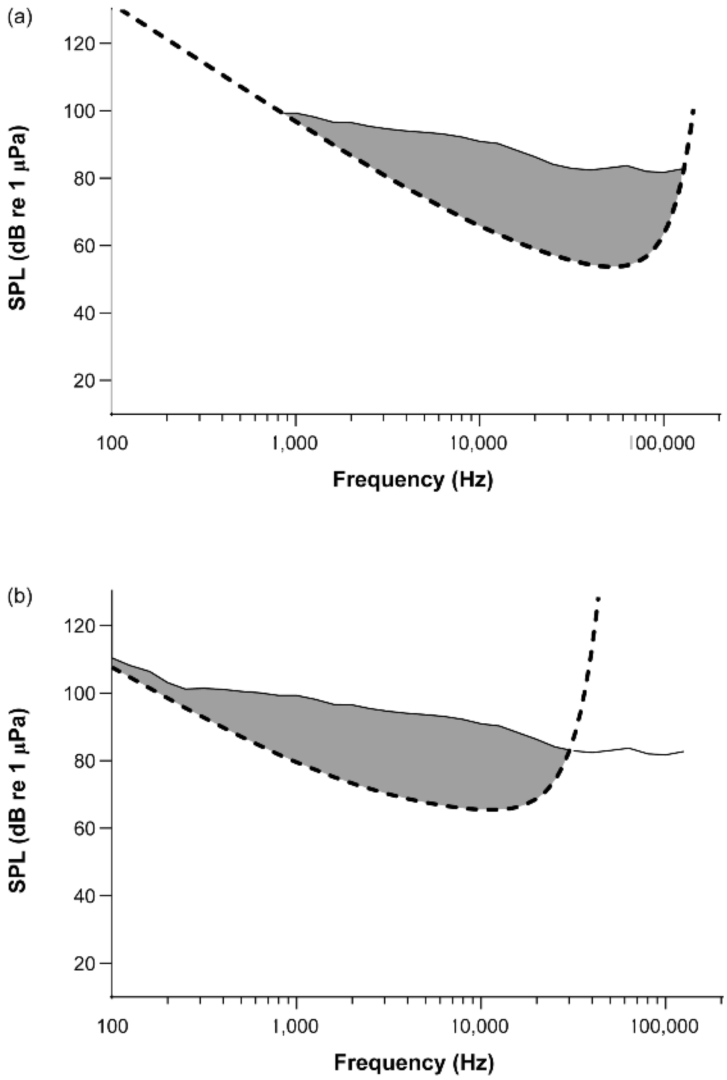
Figure 7



(a) Comparison of OTO_{gm} of the main holding pools to the composite audiogram for mid-frequency odontocetes (National Marine Fisheries Service 2016). The shaded region depicts the frequency range where the potential for masking occurs, assuming functional bandwidths of the odontocete ear are ~1/3-octave. (b) Comparison of OTO_{gm} of the main holding pools to the composite audiogram for otariids (National Marine Fisheries Service 2016). The shaded region depicts the frequency range where the potential for masking occurs, assuming functional bandwidths of the otariid ear are ~1/3-octave.

this purpose, the mid-frequency odontocete composite audiogram and the underwater otariid composite audiogram developed as part of the National Marine Fisheries Service (NMFS) technical guidance for assessing the impact of anthropogenic sound on marine mammals were used (National Marine Fisheries Service 2016). The composite audiograms were used instead of individual audiograms in order to create a representative curve for species within a particular hearing group. The curves include representatives of the marine mammals most commonly held by the marine mammal display community: the mid-frequency odontocete hearing group includes the bottlenose dolphin and beluga, and the otariid hearing group includes California sea lions. Figure 7 compares the composite audiograms to the OTO_{gm} for the main pools but only across the range of hearing identified by the composite audiograms. The shaded region in each graph denotes the frequencies at which the OTO_{gm} exceeds the detection threshold for pure tones: for mid-frequency odontocetes, the range is from ~1–125 kHz; for otariids, from 0.1–30 kHz. At the regions of best hearing, the differences between OTO_{gm} and threshold are ~30 dB and ~25 dB for the mid-frequency odontocetes and otariids, respectively. Based on these comparisons, the potential for substantial masking of communication signals and echolocation within the enclosures and under ambient noise conditions appears unlikely. Mean source levels of bottlenose dolphin whistles have been reported to range from 138–158 dB re 1 µPa (Janik 2000; Jensen *et al* 2012; Frankel *et al* 2014), which is sufficient for the communication space provided by most enclosures. Similarly, given the source levels of echolocation signals (> 180 dB SPL peak-peak), and the distances over which echolocation might be utilised (as bounded by the enclosures), there is little potential for the masking of returning echoes by the ambient noise of the enclosures. Under typical noise conditions, the potential for masking likely only exists for signals near the threshold of detection. Even in these circumstances, the degree to which masking might truly occur will depend on the extent to which ambient noise conditions are co-modulated, which could provide a significant release from masking relative to Gaussian noise sources (Branstetter & Finneran 2008; Trickey *et al* 2010). Furthermore, if some degree of masking were to exist, the impact to marine mammals under human care would remain unclear, since predation, foraging, and navigation are not of survival concern under these conditions.

The potential impact of irregularly or periodically occurring sound sources at facilities (eg gate operations, mobile platform operations, scrubbers) should be considered on a case-by-case basis, not as part of the persistent ambient noise. A characterisation of all the potential noise sources to which marine mammals under human care might be exposed is beyond the scope of this effort. However, as noted here, considerable variability in the noise characteristics of devices potentially used in and around marine mammal facilities exists, and the levels, spectral characteristics and durations of operations should be considered in context of the hearing capabilities of the exposed animals. Careful thought needs to be given to the potential for noise to enter pools through unobvious means. For example, during the assessment of one set of pools, minor construction was occurring several tens of meters away. The sound of hammering was clearly audible underwater as it was coupled into the pool through the ground and surrounding concrete. The potential for disturbance to marine mammals under human care from sound sources, such as these, should be considered as they might be unpredictable (to the animal), potentially novel, and might not be easily localised to a source. Long-term monitoring of enclosures is now technologically feasible and would enable facilities to better characterise the variability in the noise to which their marine mammals are exposed and to identify potentially problematic noise sources. This would be particularly important for identifying those noise sources with the potential to cause auditory fatigue, stress, or behavioural disruption.

The survey presented here suggests that most marine mammal facilities have ambient noise levels similar to many of the coastal environments inhabited by species typically kept by humans (eg bottlenose dolphins, California sea lions). Furthermore, facility ambient noise levels, regardless of facility type (land-based pools, semi-open, and open-enclosure), generally appear to be sufficiently low so as not to interfere with animal communication. Nevertheless, facilities and pools should be considered individually and monitored regularly; although the vast majority of pools assessed in this survey demonstrated acceptable noise profiles, the occasional pool was found with a noise issue. These consisted of either elevated low-frequency noise or the presence of tonal signals, which were too low to be harmful to hearing but could be considered a source of annoyance or stress. In all instances, the source of noise was correctable. It is therefore recommended that facilities conduct a periodic evaluation of their enclosures to ensure that noise levels are commensurate with the goal of promoting the welfare of marine mammals under their care.

As a final point of consideration, it should be noted that the statistical representation of sound (means, standard error, maximum/minimum) used in this study is not the only relevant statistical representation, even though it conforms to prior recommendations (eg means and standard deviations of sound pressure levels, as described in ANSI/ASA 2016). Other statistical representations can be made, including percentiles, confidence intervals, means and quartiles, etc. None of these approaches to characterising noise are incorrect. However, as concern for the acoustic welfare of marine mammals under human care increases, it will be important that standardised approaches for measuring noise in marine mammal facilities be considered so that welfare issues can be discussed relative to a consistent statistical representation of noise. Such guidance will also be needed for facilities engaging in long-term monitoring of noise conditions within their marine mammal enclosures so that monitoring results are consistently represented across facilities.

Animal welfare implications

Most marine mammals have sensitive underwater hearing and for some marine mammals hearing is the primary means of sensing the environment. The welfare of marine mammals under human care should consider the acoustic environment in which marine mammals are kept, as underwater noise might not be apparent to keepers listening in air and/or noise might be at frequencies well above the human range of hearing (ultrasonic) but within sensitive regions of marine mammal hearing. Little reporting on the underwater noise in marine mammal enclosures exists. Although the survey conducted here suggests that the underwater noise within marine mammal enclosures is likely not problematic in most cases, occasional issues that were discovered argue for periodic underwater acoustic monitoring of enclosures to ensure that noise does not exist that could negatively affect marine mammal welfare. Facilities with identified noise issues should take into consideration the frequency range and sensitivity of hearing of the animals contained in the enclosures and implement appropriate remediation or mitigation procedures.

The survey reported here was based on a cross-sectional design (ie many facilities and pools) with a focus on capturing the typical ambient noise of the pools. Measurements were intentionally attempted in the absence of activities that might otherwise temporarily elevate noise (eg construction, animal vocalisations). For this reason, research is needed to determine what the maximum levels of sound might be in marine mammal enclosures and to develop appropriate measures for mitigating animal noise exposure should high-level anthropogenic noise be anticipated. As previously noted, this will require long-term monitoring efforts to adequately characterise the variability in noise exposure. Effort is also needed to determine what types of acoustic signals elicit negative behavioural responses in marine mammals or that might contribute to stress. The impact of the acoustic environment on the welfare of marine mammals under human care is in its infancy and more targeted studies are needed to continue acquiring information for use in developing and improving welfare practices.

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