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Marine soundscape planning: Seeking acoustic niches for anthropogenic sound

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Abstract

Both marine mammals and hydroacoustic instruments employ underwater sound to communicate, navigate or infer information about the marine environment. Concurrent timing of acoustic activities using similar frequency regimes may result in (potentially mutual) interference of acoustic signals when both sources are within audible range of the recipient. While marine mammal fitness might be negatively impacted upon, both on individual and population level, hydroacoustic studies may generate low quality data or suffer data loss as a result of bioacoustic interference. This article pursues, in analogy to landscape planning, the concept of marine soundscape planning to reconcile potentially competing uses of acoustic space by managing the anthropogenic sound sources. We here present a conceptual framework exploring the potential of soundscape planning in reducing (mutual) acoustic interference between hydroacoustic instrumentation and marine mammals. The basis of this framework is formed by the various mechanisms by which acoustic niche formation (*i.e.*, the partitioning of the acoustic space) occurs in species-rich communities that acoustically coexist while maintaining high fidelity (hi-fi) soundscapes, *i.e.*, by acoustically partitioning the environment on the basis of time, space, frequency and signal structure. Hydroacoustic measurements often exhibit certain flexibility in their timing, and even instrument positioning, potentially offering the opportunity to minimize the ecological imprint of their operation. This study explores how the principle of acoustic niches could contribute to reduce potential (mutual) acoustic interference based on actual acoustic data from three recording locations in polar oceans. By employing marine soundscape planning strategies, entailing shifting the timing or position of hydroacoustic experiments, or adapting signal structure or frequency, we exemplify the potential efficacy of smart planning for four different hydroacoustic instrumentation types: multibeam echosounders, air guns, RAFOS (Ranging and Fixing of Sound) and tomographic sound sources.

Introduction

Early bioacoustic research already noticed that the vocal "give and take" between species forms a characteristic feature of many natural sound environments (*e.g.*, Schafer, 1977). Krause (1993) showed that in many natural sound environments, the "biophony" (*i.e.*, the composition of sounds created by organisms; Krause (1987)) appears to piece together like a puzzle in terms of both frequency and time, leading to his "acoustic niche hypothesis." This hypothesis extends the principle of ecological niche formation (Hutchinson, 1957) to the acoustic realm. Acoustic space can be considered a limited resource within the overall ecological space. Competitive exclusion theory predicts that when resources are limited, species competing for the same resource will either become competitively excluded or partition the resource to enable coexistence (Gause, 1934). Acoustic competition may lead to a species with signals similar to a competitor's signals either losing its acoustic niche (in analogy to food and habitat niches) or modifying its signals to overcome inter-specific acoustic overlap and communication hinder. Acoustic overlap may directly or indirectly affect the fitness of the acoustically excluded species, potentially entailing *e.g.*, the loss of mating and/or foraging opportunities, unnecessary aggressive interactions and increased predation risk as well as the production of unfit hybrids in related species (*e.g.*, Bradbury and Vehrencamp, 1998; Farina et al., 2013; Bleach et al., 2015; Medeiros et al., 2017). Through selective forces senders and receivers are therefore likely to develop adaptive features reducing acoustic interference from other species as well as abiotic sources (*e.g.*, Lengagne and Slater, 2002; Putland et al., 2017). Evidence of acoustic resource partitioning is widespread among many animal taxa (see Helfer and Osiejuk, 2015), although studies have also produced mixed results (*e.g.*, Chek et al., 2003; Schmidt et al., 2013; Tobias et al., 2014; Helfer and Osiejuk, 2015). The fact that partitioning of the available communication space is also a key aspect for many technical applications, *e.g.*, assignment of radio frequencies (Shannon, 1948), illustrates the universality of the problem of overcoming signal interference when using electromagnetic or acoustic waves as means of communication.

Sound-producing species may partition the acoustic space in various dimensions. In anurans, birds and insects, calling activity between species is partitioned according to space, time and frequency (*e.g.*, Chek et al., 2003; Diwakar and Balakrishnan, 2007; Luther, 2009; Amézquita et al., 2011; Schmidt et al., 2013). Sueur (2002) showed that in cicada acoustic assemblages (a group of sound producing organisms that are in mutually constitutive and transformative relation (Ochoa Guatier, 2014)), each species exhibits distinct temporal and frequency patterns in their acoustic signals and calling height (*i.e.*, the height above ground at which cicadas produce sound) was vertically stratified between species. Partitioning of the acoustic environment by these cicada species was suggested to not only serve to avoid acoustic signal interference, but also contribute to reduce the risk of hetero-specific courting and mating. Adaptive timing of vocal activity to overcome overlap with acoustic competitors is also known to be a widely distributed ability of many songbird species (*e.g.*, Cody and Brown, 1969; Ficken et al., 1974; Popp et al., 1985; Yang et al., 2014; Wilson et al., 2016). Nightingales (*Luscinia megarhynchos*) adjust the timing of their song to their acoustic environment by inserting songs in the silent intervals between heterospecific vocalizations (Brumm, 2006). A fourth "dimension," the acoustic signal structure domain, entails the combined spectral and temporal features of the signal. In certain anuran communities, acoustic niche segregation has been shown to mainly base on the acoustic features of advertisement calls (*i.e.*, call structure), with spatial and temporal dimensions contributing less to niche segregation (Sinsch et al., 2012).

Soundscape planning

Anthropogenic additions to the acoustic environment may introduce an additional sound source with which animals have to compete for acoustic space and compensate by vocal behavioral adaptations such as changing the frequency, timing, duration or amplitude of their calls (see Brumm and Slabbekoorn, 2005 for a review). Gleaning bats avoid hunting in areas where noise was played back with main energy in specific frequency bands that were found crucial for passive sound localization accuracy (Fuzessery et al., 1993; Schaub et al., 2008). In the time domain, animals avoid acoustic interference from anthropogenic noise by shifting the timing of their acoustic activity

(Brumm and Slabbekoorn, 2005). European robins (*Erithacus rubecula*), for example, were found to reduce acoustic interference by singing during the night in areas that were noisy during the day (Fuller et al., 2007).

In analogy to the behavioral adaptations among animals, a human-mediated active avoidance of overlap between anthropogenic and animal communication sounds could offer a strategy to reduce potential acoustic overlap and interference, thereby improving soundscape quality for all users. Segregation of biotic and (intentional) anthropogenic acoustic signals can also directly benefit the purpose for which certain anthropogenic sounds are produced. For anthropogenic sound sources such as shipping, mine decommissioning and marine construction, noise is an unwanted (but to date unavoidable) by-product of operation. In the case of hydroacoustic instrumentation, the acoustic signals are introduced intentionally in the underwater environment for geophysical or oceanographic measurements or their operational support. A shared characteristic of hydroacoustic instrumentation is that the quality of the measurements relies on the quality of the received signal; interference with biological acoustic sources can generate low quality data or result in data loss. Hydroacoustic measurements often exhibit certain flexibility in their timing, signal characteristics or location of measurements, which provides a unique opportunity to explore if by smart planning and management of anthropogenic sound sources overlap with biotic sound sources can be reduced.

In the terrestrial realm, such soundscape management is referred to as *soundscape planning*. The term soundscape planning was coined in analogy to landscape planning, which involves reconciliation of competing land uses while protecting natural processes and natural and cultural resources (Brown, 2012). Soundscape planning has to date mainly been applied in urban areas to preserve traditional soundscapes or soundscape heritage from societal and physical changes by actively designing the acoustic environment, *e.g.*, by managing the distribution of sounds or restoring the soundscape composition by deliberate introduction or elimination of certain sounds (*e.g.*, Torigoe, 2003; O'Connor, 2008; Deng et al., 2009; Kang et al., 2016). Although soundscape management and planning is a growing field in the terrestrial realm, it has to our knowledge to date not been linked to the underwater environment. By translating the concept to the underwater realm, we aim to stipulate discussion and thoughts on whether the soundscape planning approach is a viable concept when designing hydroacoustic experimental setups. The basis of this conceptual soundscape planning framework as presented here is formed by the various mechanisms by which species-rich biophonic communities partition their acoustic environment to acoustically coexist. We exemplify how these mechanisms, in the context of acoustic niche separation, could contribute to reduce acoustic interference between hydroacoustic instrumentation and biological acoustic sources, based on actual acoustic data from three recording locations in polar oceans. Polar oceans offer the advantage that they are still rather devoid of ship noise and hence can be assumed to largely exhibit a relatively integer and pristine soundscape comprising intact interplays between biotic acoustic contributors.

The application of the soundscape planning concept, as described and exemplified here, exclusively focuses on disentangling biophonic and anthrophonic signals to reduce the potential of acoustic interference. The concept should therefore be viewed only as one of several potential building blocks required to address the multi-facetted issue of contingent anthropogenic noise impacts on marine fauna. Noting for example, the ongoing debate on the impact of air gun signals on marine mammals (see Gordon et al., 2003 for a review), we emphasize that the aspects considered in that discussion remain, by and large, unaffected by the eventual benefits of soundscape planning.

Polar ocean soundscapes

Marine mammals are the primary biotic acoustic contributors to most polar ocean soundscapes (*e.g.*, Ahonen et al., 2017; Menze et al., 2017). The scope of this study is therefore limited to separating the sounds produced by the different marine mammal species. Spatial and temporal differences in marine mammal species composition in polar waters preclude universal mapping of marine mammal acoustic niches and instead requires time- and location-specific evaluation in terms of marine mammals' acoustic contribution to local soundscapes. To illustrate this site-specificity, we used actual data on marine mammal acoustic assemblages from three recording locations: one in the Arctic Ocean, one in the offshore and one in the coastal Southern Ocean. The latter two serve to also exemplify local spatial dependencies.

Visual representation of three of the four dimensions based on which the acoustic space can be partitioned is provided by spectrographic box displays (SBDs) of marine mammal species acoustic presence over a fictive year. SBDs indicate the temporal distribution of acoustic presence on a daily basis (*i.e.*, daily presence/absence of marine mammal species sounds) and the frequency range of species-specific sounds based on information derived from previous in-detail analyses of the acoustic recordings (Van Opzeeland, 2010); as well as from information taken from the literature (Southall et al., 2007; Gedamke and Robinson, 2010; Risch et al., 2014). To illustrate the fourth dimension based on which the acoustic space can be partitioned, segregation based on signal structure, short-term spectrograms are employed to visualize actual individual acoustic signatures. In previous studies, variation in signal structure mainly entailed temporal structures of calls and was hence interpreted as the shortest of the temporal scales at which senders can avoid overlap (*e.g.*, FTO, fine temporal overlap, (Jain et al., 2014)). However, given that marine mammal calls exhibit more complex acoustic features (*i.e.*, frequency and amplitude modulation), which could aid signal separation, we here treat signal structure as a separate "dimension."

Recording locations

The offshore Antarctic data were obtained with an AURAL M2 (Multi-Électronique) which was moored at 66°01' S and 00°05' E and recorded over an overall duration of 2.8 years (1,015 days). See Menze et al. (2017) for detailed information on recording settings. Figure 1 shows a long-term spectrogram (LTS) of the total recording from this location, with some of the marine mammal species-specific energy contributions delineated by the grey boxes. In the LTS, the timing of acoustic

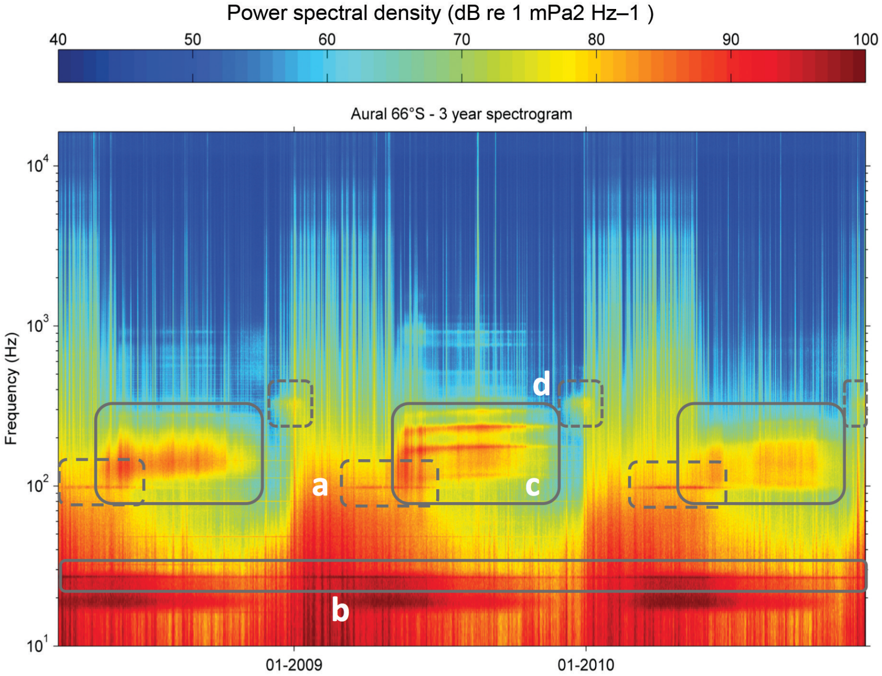

Figure 1. Long-term spectral average (LTSA) of recordings from the pelagic Antarctic recording site (Menze et al., 2017).

Boxes indicate (by occurrence *left to right* and *top to bottom*) the vocalization range of: (a) fin whales, (b) Antarctic blue whales, (c) Antarctic minke whales and (d) leopard seals.

onset of species as well as development of species composition over time shows relatively little interannual variation. Species-presence information could therefore be condensed into a single fictive year, represented by an SBD with detailed species presence information obtained by visual and auditory inspection of spectrograms of 5-minute long recording segments in Adobe Audition 2.0.

The Antarctic coastal SBD is based on analysis of near-continuous underwater recordings collected by PALAOA (Perennial Acoustic Observatory in the Antarctic Ocean, see Boebel et al., 2006 for details and map), which is located on the edge of the Ekström Iceshelf (70°31' S 8°13' W), Antarctica. Alongside biophonic contributions from ten marine mammal species, geophonic events (*e.g.* turbodites), glacier calving and storms also characterize the local soundscape. Marine mammal species presence information was derived from previous analyses of several years of PALAOA recordings (see Van Opzeeland et al., 2010, 2013; Van Opzeeland, 2010) and also combined into the SBD of a fictive year.

The information on marine mammal acoustic presence for the Arctic recording location (central region of the Bering Strait) was derived from Miksis-Olds et al. (2010) based on a 1-year long recording. The reader is referred to this publication for further details on recorder specifications and data analyses. Multi-year operation of passive acoustic recorders in this region has shown that the interannual invariability of this specific soundscape is relatively low with respect to the acoustic occurrence of the major marine mammal contributors (*e.g.*, Woodgate et al., 2015). The single year of data used here is therefore assumed to represent the local marine mammal acoustic assemblage.

Soundscape planning applied

As soundscape planning tool, we propose a region-specific systemic screening of the anthropogenic and biotic signals' characteristic for *spatial, temporal, spectral and signal characteristic overlap* and to seek — if conceivable — operational and technical approaches to reduce or eliminate overlap. To explore this tool's real-world applicability, we here focus on air guns, multi-beam echosounders, as well as tomographic and RAFOS sound sources, as these are illustrative of the range of signal characteristics and spatial scales over which hydroacoustic sound sources are employed (Figure 2 and Table 1). They are, in fact, also actually employed in polar oceans. For more in-depth information on hydroacoustic

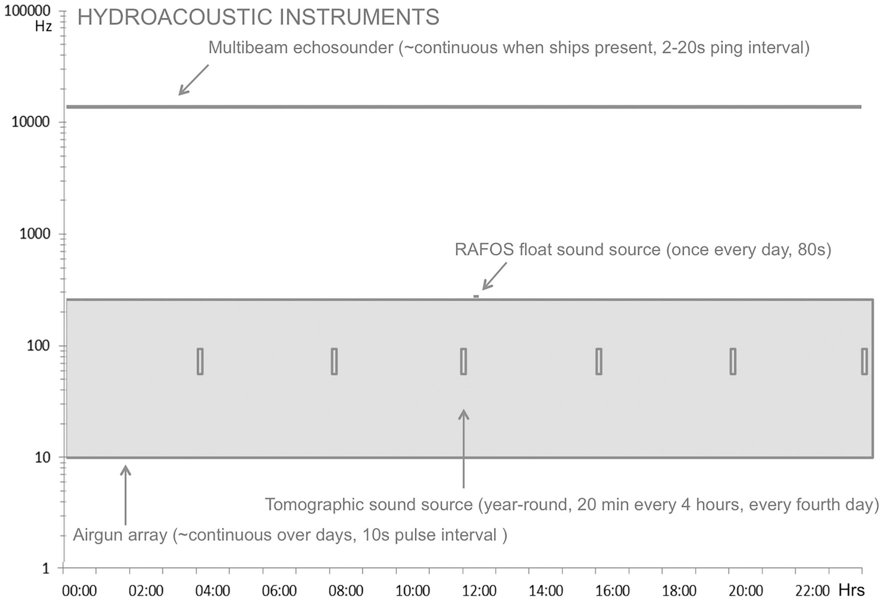

Figure 2. Schematic representation of operational frequencies and times of four hydroacoustic instrumentation types on a fictive day.

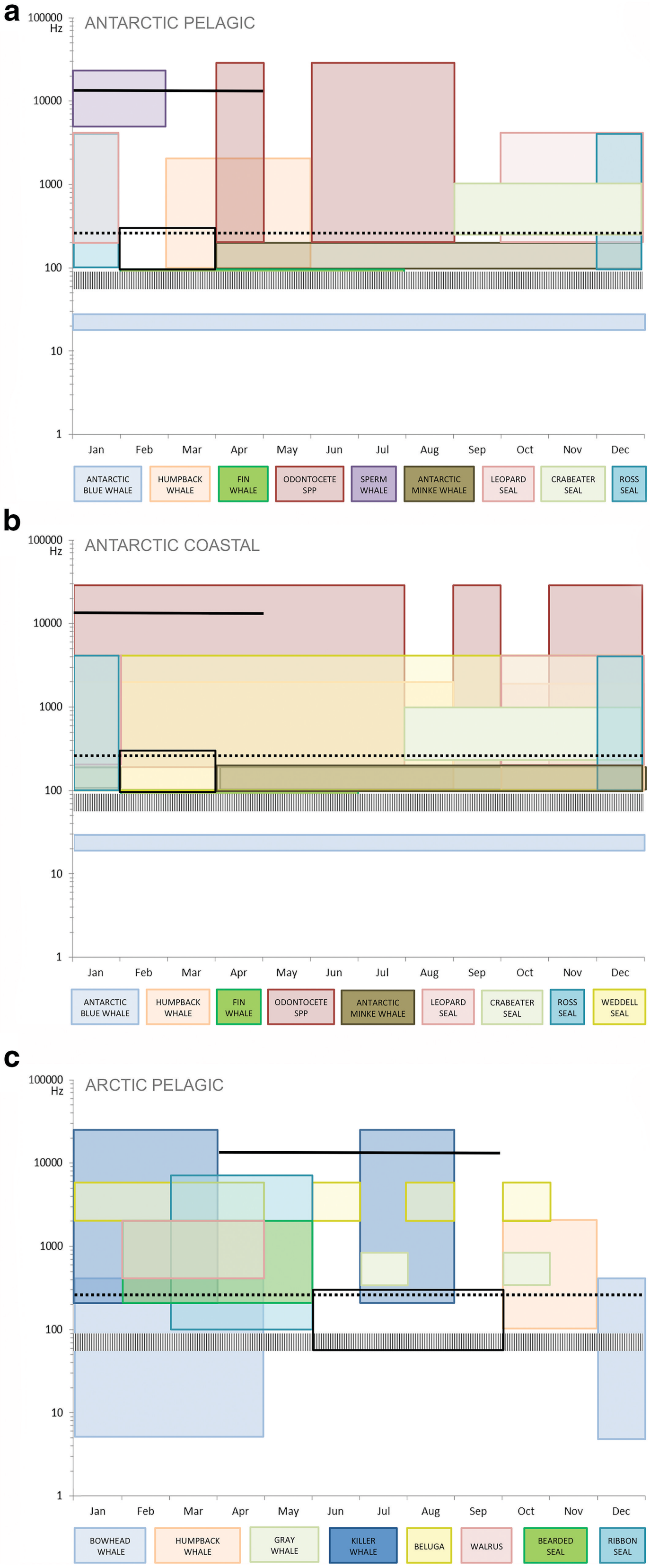

Figure 3. Spectrographic Box Displays (SBDs) for three recording locations.

(a) Antarctic pelagic, (b) Antarctic coastal and (c) Arctic. Colors indicate the timing and frequency characteristics of the species acoustically present at each location. Typical operational periods and frequencies of hydroacoustic instrumentation comprise: multibeam echosounder (*solid black line*), RAFOS sound source (*dotted black line*), seismic airgun-array (*black square*) and tomographic sound source (*grey dashed band*).

Table 1. Signal characteristics and duty cycles by source. Note that experiments may comprise multiple sources or that multiple surveys might be conducted in audible distance from a given location.

Source	Operational frequency	Signal duration when emitted	Typical deployment duration	Duty cycle (during peak operation period)	Daily presence per year	Duty cycle (averaged over 1 year)	Order of audible range[5]
Air-gun	10 Hz–1 kHz	0.01 s[1]	1 month	<0.1%[1]	8% (1 month)	<0.008%	100 km
Multibeam echosounder	15.85 kHz	0.1 s	1 month	3%[2]	8% (1 month)	0.24%	1 km
Tomographic source	75 Hz	1,200 s	1 year	8%[3]	25% (every 4th day)	2%	1,000 km
RAFOS source	260 Hz	80 s	2 years	<0.1%[4]	100% (every day)	<0.1 %	100 km

1 Signal length (10 ms) divided by repetition rate (10 s).
2 Total signal length (100 ms) divided by repetition rate (3 s).
3 Six signals of 20 minutes duration per day.
4 Signal duration 80 seconds, once daily.
5 At depths where marine mammals vocalize at similar frequencies as signal.

instrumentation (*e.g.*, sound levels) we refer to comprehensive reviews by Hildebrand (2009), Williams et al. (2015) and Boebel et al. (2018).

As basis of the screening and discussion, we superpose the various instruments' operational and spectral characteristics to the SBDs for the Arctic and two Antarctic locations (Figure 3a–c) visualizing if and in what dimension signal overlap between marine mammals and hydroacoustic instrumentation might occur. The order and extent to which spatial, temporal, spectral and signal characteristic overlap is discussed is determined by their significance for the marine soundscape planning approach and hence differs per instrumentation type.

Air guns

Air gun arrays are used in oil and gas exploration and geophysical research to map the geologic structures below the sea floor. Air guns abruptly release a volume of air underwater, creating a sound wave which reflections from the sediment contain information on *e.g.*, crustal or sedimental structures. Downward directivity of the emitted wave is achieved by phased triggering of multiple air guns to produce a directed pulse of sound. However, in spite of this directivity, air guns nevertheless also emit high sound pressure levels towards the horizontal axis. Figure 2 depicts the operation of an air gun as grey bars, in this example producing pulses between 10–245 Hz at a 10 s repletion rate.

Spectral overlap

Air gun signals bear the bulk of their energy in the low frequency range (<100 Hz) (Figure 4). Recordings from Fram Strait (Arctic) show that bowhead whale (*Balaena mysticetus*) (Breitzke et al., 2008) vocalizations occupy the 330–550 Hz band with additional components above 1 kHz (Figure 5a) and hence experience no spectral overlap from seismic signals. In the case of fin whales (*Balaenoptera physalus*), downsweep calls at 20–30 Hz and at 130 Hz are spectrally overlapped to 100% by the concurrent seismic pulses (with sound pressure levels exceeding background noise levels up to 245 Hz), while the fin whale call (122–133 Hz) and (20–30 Hz) overlaps 9 % of the seismic spectrum (Figure 5b).

Recently, bandwidth-controlled seismic sources have been developed to reduce the environmental footprint of air guns (*e.g.*, Li and Bayly, 2017). These so-called "esources" reduce unwanted energy by

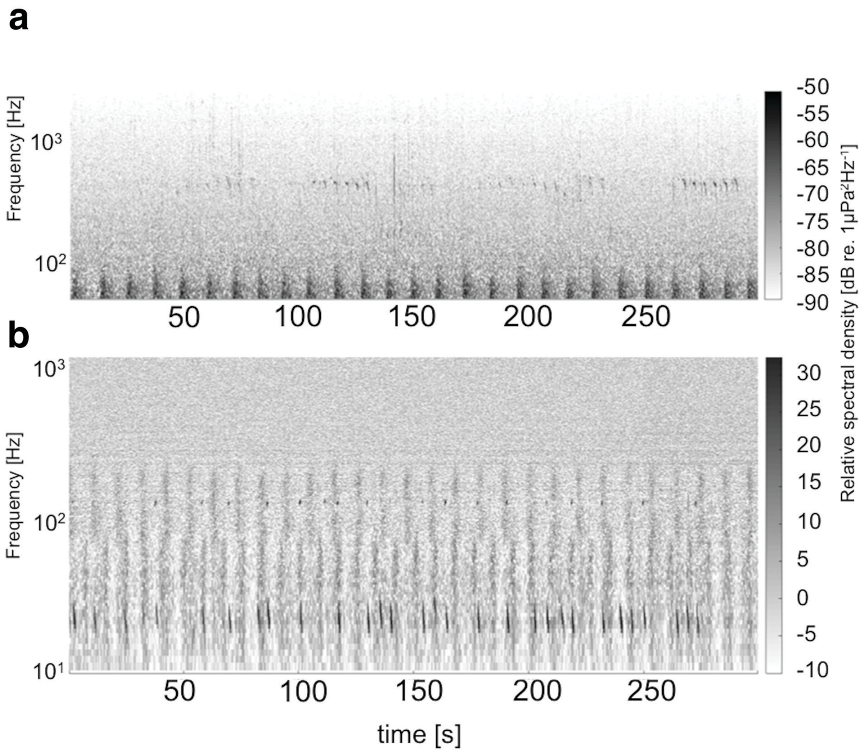

Figure 4. (a) 5-min long spectrogram of acoustic environment in Fram Strait on 14 November 2012. Bowhead vocalizations are discernable between 330 and 550 Hz, seismic pulses at frequencies below 100 Hz. (b) 5-min long spectrogram of acoustic environment in Fram Strait on 8 July 2012. Fin whale vocalizations exhibit a distinct pulse at 130 Hz and a downsweep between 20 and 30 Hz, while seismic pulses are observed at intervals of 10 s covering the frequency range below 245 Hz.

Note the different y-scaling.

suppression of high-frequency content outside of the main seismic bandwidth and have been shown to perform well compared with industry standard conventional seismic sources and may provide a possibility to reduce overlap with marine mammal sounds above ~200 Hz.

Spatial overlap

Geophysical experiments involving operation of air guns are usually bound to areas that are of specific interest and relocation of the study site is therefore not to any significant extent possible.

Signal structure overlap

Seismic signals, when emitted, are short pulses (10 ms). Propagation of such signals to greater distances results in a loss of associated sound pressures (transmission loss) but may also cause a temporal broadening of the signal (to about 20–40 ms in the example shown in Figure 4). Fin whale 20 Hz pulses are of similar duration, down-sweeping from 30 Hz to 20 Hz, and hence their signatures are 100% overlapped in shape by the broadened seismic signals. Overlap of the two signals is somewhat reduced due to their different repetition rates: 10 s for seismic pulses and 24 s for fin whale pulses.

Temporal overlap

With air guns necessarily being towed by a survey vessel, operation of air guns in polar waters is restricted to periods when the ocean is ice-free (Antarctic: February–March; Arctic: June–September).

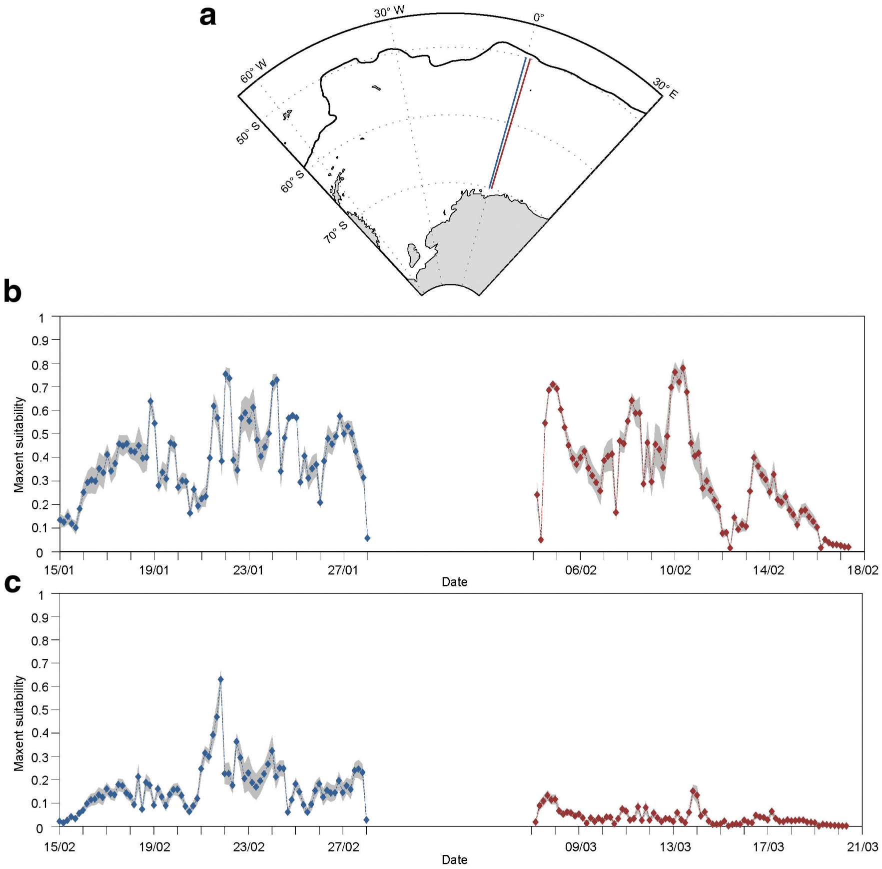

Figure 5. (a) Hypothetical layout of a seismic survey conducted along two transect lines from North to South (blue) and South to North (red). (b) Habitat suitability values for humpback whales at the time and location of the hypothetical ship for a survey from 15 January to 17 February 2007. (c) Habitat suitability values for humpback whales at the time and location of the hypothetical ship for a survey from 15 February to 20 March 2007. The standard deviation is depicted by the grey shading.

Taken from Bombosch et al., 2014 with permission.

In spite of this restriction, regional differences in the timing of animal signaling may provide windows during which overlap between operation of hydroacoustic instrumentation and marine mammal vocalizations can be reduced. Figure 3a and b show substantial differences between the Antarctic coastal and the offshore recording sites in their extent of spectral and temporal overlap between marine mammal vocalizations and air guns during the period that air guns can be operated. At the offshore site, a potential window exists in February, when no spectral overlap occurs with the species present. Most scientific geophysical studies are of relatively short duration so that the timing of experiments can anticipate the spatio-temporal patterns in marine mammal distribution. For example, odontocete whales are present at both Antarctic recording locations, but the pattern in timing of acoustic presence differs markedly between both sites (Figure 3a and b). In cases where experiments are carried out at multiple sites, certain flexibility in the order in which areas are visited could further aid to prevent overlap between hydroacoustic and marine mammal acoustic signals. Bombosch et al. (2014) developed the concept of dynamic habitat modeling as a pre-cruise planning tool for seismic surveys, producing daily prediction maps that showed considerable changes in habitat suitability throughout the season for baleen whale species. Information on spatio-temporal distribution patterns can provide valuable insights to help adjust the timing of hydroacoustic activity to periods when it is least likely to encounter a given species in the area of interest to the experiment (Figure 5).

Multibeam echosounders

Deep-water multibeam echosounders are installed on mid-sized to large survey vessels to allow mapping a swath of the seafloor faster and more accurately than by singular depth soundings from traditional echosounders. A multibeam echosounder employs a complex array of active transducers, creating a highly directional emission pattern (Figure 6). While the frequency of pings may vary slightly between different echosounder types and further depend on the depth of the water being mapped, we here consider a multi-beam echosounder suitable for deep waters with a train of pings emitted at depth-dependent intervals ranging from *e.g.*, 2 to 20 s (Figure 2). Such multibeam sonars are shipborne and, similar to airgun operations, the presence of multibeam sonar will in most cases be restricted to the period when the ocean is largely ice-free.

Spectral overlap

A commercially available multibeam echosounder system is the Hydrosweep DS 3 multibeam echosounder, operating at 15.8 ± 0.25 kHz (Figure 6). This frequency is higher than the frequency bands actively utilized by the majority of pinniped and baleen whales, and is well below the frequencies employed by odontocete species, with the prominent exception of sperm whales (*Physeter macrocephalus*), producing clicks with centroid frequencies of 15 kHz (Møhl et al., 2003). While sonar signals feature a bandwidth of less than 4 kHz, the sperm whale click spans a substantially broader bandwidth of about 10 kHz (visually estimated from Figure 9 in Møhl et al., 2003). Hence, the sperm whale pulse spectrally overlaps the echosounder signal by 100%, while the echosounder overlaps up to 40% of the sperm whale click, potentially causing mutual interference.

Signal structure overlap

Both, Hydrosweep DS 3 signals and sperm whale clicks are relatively similar from a signal processing point of view; both emit short pulses, *i.e.* tens of milliseconds in duration for sonar and order of 100 µs duration pulses for the sperm whale. Most recently, Hydrosweep DS-3 was upgraded to also include chirp signals (FM-AM modulated pulses), which might overcome this similarity at least from the sonar's perspective. The extent to which the acoustic perception or behavior of sperm whales might actually be impacted on by overlapping sonar pings and chirps is not known.

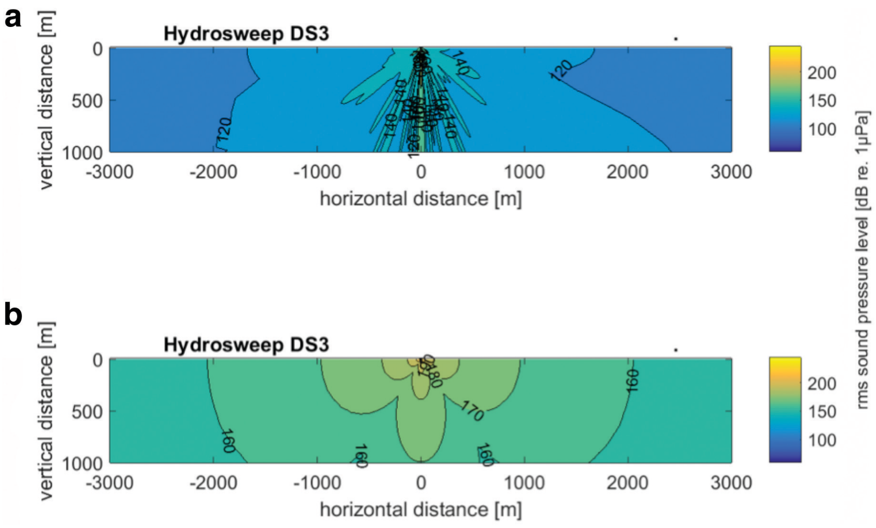

Figure 6. Spatial representation of sound pressure levels along-ship (a) and athwart-ship (b) for an Atlas Hydrosweep DS-3 multi-beam sonar.

Temporal overlap

The use of multibeam echosounders is limited to dedicated research expeditions, generally lasting between several days to weeks. Sperm whales, on the other hand, produce clicks in search for prey year-round. Operation of ship-born echosounders is for most ships restricted to periods during which the region is (relatively) ice-free, which limits the flexibility in timing of this source. On a seasonal scale, no distinct time slot can be identified, during which conflicting use of this frequency band can be avoided. The same holds true on a diel time scale given that both sperm whale foraging and sonar surveying occurs on a 24/7 scheme. None of the (temporal, structural, spectral) signal traits therefore provides a possibility to acoustically separate sperm whale clicks and multibeam echosounder signals.

Spatial overlap

At the regional scale, for the offshore Antarctic location (Figure 4a), the acoustic presence of sperm whales overlaps in frequency, time and signal structure with the multibeam echosounder signal during the period that the area would be accessible to ships (February–March). However, at a local scale, multibeam sonar emissions are oriented primarily athwart-ship with strong along-ship dampening, which, given the increased acoustic absorption at high frequencies of the pings, results in relatively limited volume of ensonification (Figure 7). Therefore, sonar signals are relatively unlikely to interfere with the acoustic activity of individual sperm whales as long as these are not within a few kilometers distance from the ship. Additionally, as the sperm whale emits its clicks to elicit echoes from prey nearby, it most likely anticipates these echos, which likely adds to their distinguishability from the uncorrelated sonar pulses.

In summary, while probably only changes of the sonar ping's spectral characteristic might be a way of reducing acoustic overlap in general, this source's limited range on the other hand most likely already leverages its potential to overlap with bioacoustic signals.

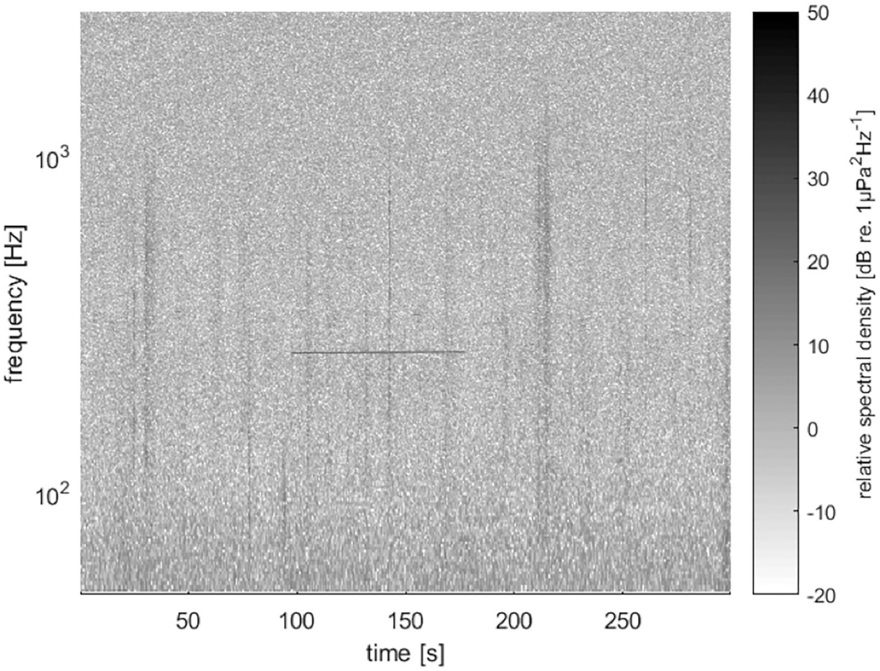

Figure 7. Five min-long spectrogram of underwater sound including a RAFOS signal (the thin nearly horizontal line, a 80 s long linear sweep from 259.375 to 260.89 Hz) as emitted by a RAFOS source moored at 800 m depth and recorded by a passive acoustic recorder moored at 53 km distance from the source.

Tomographic signals

Tomographic sound sources are operated at various (usually low) frequencies and in a variety of modes. ATOC HX-554 (Howe et al., 1995) is chosen as example here, emitting a relatively broadband sweep centered at 75 Hz (frequency range 57–92 Hz), as represented by the 6 vertical bars in Figure 2. For the tomographic experiments assumed here, six 20-min transmissions are emitted at 4 h intervals once every fourth day for the duration of one year. Ocean acoustic tomographic experiments are carried out to gain information on ocean temperatures and velocities across ocean basin scales. By precisely measuring the time it takes for an acoustic signal to travel from the source to the receiver, the speed of sound and sound path can be retrieved and from this ocean temperature. Tomographic instruments operate autonomously and their operation is therefore independent of ice conditions (even though sea ice may affect system performance), allowing measurements to be conducted year-round. For these instruments, reducing acoustic interference will be at the direct benefit of the hydroacoustic study, as these are precision measurements with relatively infrequent transmissions.

Spectral overlap

Flexibility in the operating frequency of tomographic sound sources (50 Hz to 1,000 Hz) may offer an opportunity in selecting the frequency band conflicting least with regional marine mammal vocalizations. In the Antarctic, the 30–95 Hz frequency band between Antarctic blue whales (*Balaenoptera musculus intermedia*, ~15–30 Hz) and fin whales (~15–25 Hz and ~95–105 Hz) is vacant year-round (Figure 3a and b) and could in this case potentially be used for this specific (fictive, given that research using tomographic sound sources is to our knowledge not currently implemented in the Southern Ocean) tomographic signal, however the situation differs for the Arctic site (Figure 3c, revealing overlap with bowhead whale vocalizations). Furthermore, for tomographic sound sources that operate at higher frequencies (*e.g.*, 200–300 Hz, Morozov et al., 2016) both Antarctic recording locations there is a strong frequency overlap between such a fictive tomographic sound source and Antarctic minke (*Balaenoptera bonaearensis*) and fin whale signatures (Figure 3a and b).

Temporal overlap

Currently, 8% of the overall daily (*i.e.*, on transmission days) temporal acoustic space would be occupied by tomographic signals (M-sequences, Table 1, see Munk et al., 1994 for spectrograms). For both Antarctic recording locations, entire Antarctic minke and fin whale call bouts (typically lasting up to 10 minutes, *e.g.*, Stimpert et al., 2015) may be overlaid by the 20-min long tomographic signal (Figure 3a and b). Reversely, potentially simultaneously occurring biophonic signals might impede the quality of tomographic signals.

Given that the timing of tomography sweeps is relatively flexible, this, to some extent, may offer an opportunity to separate the hydroacoustic from the marine mammal signatures. On a diel scale, hourly fluctuations in Antarctic minke whale vocal activity (*e.g.*, Menze et al., 2017) can offer a window during which mutual interference can at least be reduced. Whether the tomographic transmissions may be shifted to *e.g.*, daytime only, without risk of biasing the measurement results, requires input from tomographic specialists.

Signal structure overlap

When acoustic signatures of tomographic transducers and fin and Antarctic minke whales are compared on a finer temporal scale (*i.e.*, 5 minute spectrograms), the whale repetitive pulse trains differ substantially from the 20-min long frequency modulated tomographic signal (M-sequence). The differences in signal form (*i.e.*, sequence of tonal vs. pulsed signals) may contribute to relieve mutual acoustic interference in spite of simultaneous acoustic presence of acoustic sources that also overlap in frequency.

Spatial overlap

Some tomographic experiments, at least if 2D only, exhibit a certain degree of positional flexibility in acoustic source placement. Informed positioning of the sound source may help to reduce overlap with marine mammal vocalizations when the tomographic sound source is positioned outside marine mammal acoustic hotspot areas.

For the Arctic recording location, a strong overlap between the tomographic signal and the acoustic presence of bowhead whales is evident from the SBDs of both signals (Figure 3c). Given the potential of significant mutual interference since bowheads produce sweeps in the similar frequency range as tomographic sound sources, shifting the position of receiver and transmitter, if possible, may in this case aid signal separation. In particular for sources such as the latter two, where overlap is so extensive in time and frequency, efforts to untangle acoustic signals have the potential to significantly enhance the quality of the acoustic environment for both marine mammal and hydroacoustic communication.

RAFOS signal

RAFOS (Rossby et al., 1986) is a technology developed to track free-drifting hydrographic sondes (Klatt et al., 2006), such as certain types of Argo floats (Roemmich et al., 2009), which float freely at depth (typically 1,000 m) to map interior ocean currents. RAFOS comprises a set of moored acoustic sources and RAFOS receiver equipped floats, which detect the acoustic signals emitted by the moored acoustic sources. From the arrival times of signals from two or more sources at the float, the position can be derived and its movement tracked in time. From these trajectories, the motion of water in the ocean can be derived to obtain insight into the overall ocean circulation. Currently two different RAFOS signals (at 260 Hz and 780 Hz) are in use at different locations globally. Figure 7 shows a 260 Hz RAFOS sweep, as emitted once every 24 hours by sources in the HAFOS (Hybrid Antarctic Float Observation System; Reeve et al., 2016; Figure 2) array in the Weddell Sea. RAFOS sound sources and receivers operate autonomously, are therefore independent of ice conditions and operate year-round (although here too, ice cover impacts negatively on performance).

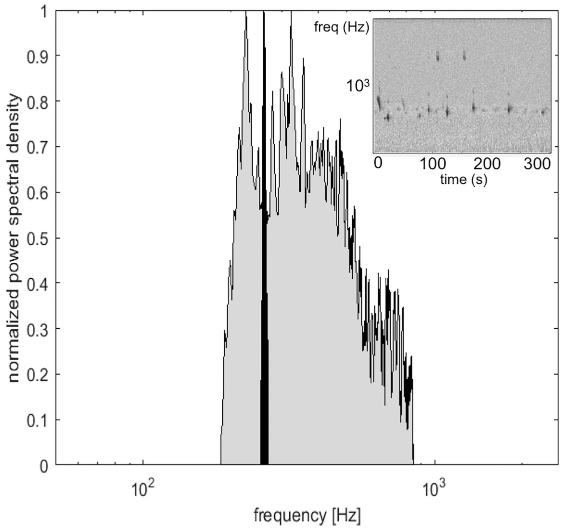

Figure 8. Normalized (to recorded peak intensity) spectrum of a RAFOS signal (black) and sequence of leopard seal vocalizations (inset image) in grey.

Inset image: Five min-long spectrogram depicting several leopard seal vocalizations recorded by the PALAOA station at the Antarctic ice shelf edge.

Spectral overlap

In the Antarctic, the 260 Hz RAFOS system is implemented as this promised better acoustic coverage throughout the Weddell Sea. Figure 3a and b show that for the Antarctic recording sites, marine mammal vocalizations overlap the RAFOS signal completely, while RAFOS overlaps only a small portion of several biotic bands. Scrutiny of these signatures reveals, that overlaps are mostly in the call's peripheral spectral part, with leopard seal vocalizations being the prominent exception. As can be recognized from Figure 8, leopard seals produce the bulk of their spectrally distributed vocalizations in a similar frequency range as the RAFOS signal, which is why we continue by focusing on this species.

Figure 8 displays spectra of the RAFOS signal (black) and the spectral sum of the relevant leopard seal vocalizations, both normalized to peak intensity. Clearly, the RAFOS signal is fully (100%) overlapped in frequency space by leopard seal low double and low descending trills (spanning 185 to 844 Hz here). While some individual vocalizations reside outside the

RAFOS band, the variability of calls results in the sum of calls completely covering the RAFOS frequency band. Reversely, the RAFOS signal covers only a small part (1.5 Hz out of the bandwidth of 659 Hz, *i.e.*, 0.2%) of the frequency band used by leopard seals. Overlap is more pronounced when compared against single call types, however, the leopard seal call types that overlap with the RAFOS signal have a bandwidth between 140 and 240 Hz (Klinck, 2008) and therefore less than 2% of the call would be spectrally overlapped by RAFOS.

RAFOS signals could, in principle, be shifted in frequency space. However, sources with lower frequency require larger resonators (scaling with the wavelength of the emitted signal) and more energy, rendering them more costly and cumbersome to handle. Sources with higher frequency (like the 780 Hz RAFOS source) result in smaller acoustic ranges, requiring more moorings to cover the same area, increasing costs and operational effort.

Temporal overlap

With RAFOS signals being required year-round (Table 1) to track under-ice Argo floats, particularly through the winter time, no opportunity exists to seasonally separate these signals from leopard seal acoustic presences. However, on a diel scale, hourly fluctuations in leopard seal vocal activity can offer a window during which mutual interference can at least be reduced. Given that the timing of RAFOS sweeps (once daily) is relatively flexible with regard to time of day at which they are emitted, partitioning the acoustic space on the diel scale offers an opportunity to at least to some extent separate the hydroacoustic from the marine mammal signals.

Within the HAFOS (Reeve et al., 2016) array of RAFOS sound sources, the concept of soundscape planning already found a first application in this context. Based on previously acquired information on diel patterns in acoustic behavior of leopard seals at this location (Van Opzeeland et al., 2010), the timing of the RAFOS sound source sweep was shifted from around midnight to noon when leopard seal calling activity was found to be lowest, reducing temporal overlap as much as possible.

Spatial overlap

Experiments employing RAFOS sound sources may exhibit a certain degree of (horizontal) flexibility in their positions, which may offer an additional possibility to separate RAFOS from marine mammal acoustic activity. The degree of positional flexibility of the instrumentation is, however, constrained by the need to acoustically cover the area where floats are expected to drift and the acoustic range of the sources. Seeking to avoid placing a source in a marine mammal hot spot is probably the most efficient approach, although in the case of leopard seals, calls have been recorded throughout the Weddell Sea during austral summer (Spiesecke et al., 2017). Placing RAFOS sources at greater depths (*i.e.*, 800 m) would reduce the acoustic overlap with leopard seals. Transmission loss reduces the RAFOS signal by about 40–60 dB prior to reaching the upper ocean realm where leopard seals vocalize (upper 30 m, Krause et al., 2015), thereby potentially already reducing its interfering potential for leopard seals.

Signal structure overlap

When acoustic features of the RAFOS signal and leopard seal vocalizations are compared on a signal structure level, the leopard seal calls exhibit a substantially different call structure than the tonal RAFOS sweep (see Van Opzeeland et al., 2010 for detailed spectrograms of leopard seal calls). The differences in signal form (*i.e.*, the RAFOS tonal sweep vs. the leopard seal pulsed signatures — as evident from the "banded" structure in calls) may contribute to relax mutual acoustic interference in spite of simultaneous acoustic presence of acoustic sources that overlap in frequency.

Discussion and outlook

The concept of underwater soundscape planning addresses the importance of considering sounds in their relevant acoustic and ecological context, while taking into account that the acoustic environment is the result of a dynamic interaction of the contributing sources. Over longer time frames, climate change, baleen whale populations recovering from whaling as well as advances in marine measurement technologies are all factors that can significantly alter the dynamics of underwater marine acoustic environments. The purpose of this first conceptual approach is however, to elaborate the idea of underwater soundscape planning and explore possibilities by which signals can be segregated at the benefit of both marine mammals and hydroacoustic research. We emphasize that the soundscape planning approach would not replace common mitigation measures of anthropogenic activities that involve active underwater sound production. Rather, it is intended as an additional tool in the planning phase of hydroacoustic research activities using spatio-temporally relevant information to identify (periodically) vacant acoustic niches. Nevertheless, before this approach can find actual application, there are several aspects that need consideration and/or deserve further investigation.

Auditory masking

So far we have strictly used "*overlap*" to indicate the potential interference resulting from similarities between signals stemming from animals and hydroacoustic instrumentation, thereby deliberately avoiding the term *auditory masking*. Auditory masking occurs when the perception of one sound is affected by the presence of another (ANSI, 1994), and is not only dependent on the attenuation of signals within the acoustic environment and the characteristics and position of the signal of interest and the masker signal, but also depends on the hearing abilities of the listener. The ability to discriminate the frequency of two overlapping signals will for example, depend on the critical bandwidth of the listener's auditory system, *i.e.*, the frequency resolution or filtering of the signals within the listener's inner ear. Also in the temporal domain, signals occurring in close temporal proximity may affect their perception, depending on the characteristics of the auditory filter. On the other hand, the ability to discriminate the directionality of a sound, allows listeners to distinguish between even highly overlapping sounds (spatial release, *e.g.*, Brungart, 2001). Lastly, energetic masking can occur when the relative energy of one signal exceeds that of another. In the marine realm sound pressure levels depend dramatically on the positions of the signaler, the noise source and the receiver, and significant changes in sound levels already occur over small- to meso- spatio-scales (*e.g.*, in open waters away from boundaries order of 40 dB loss over 100 m, 60 dB loss over 1,000 m). For mobile species, changes in the relative positions of sender and masker will therefore in most cases drastically affect the level of energetic masking (Clark et al., 2009). This situation might differ for species for which positions of senders and receivers are known a-priori to be constrained, *e.g.*, to a reef. Given that including positional scenarios is beyond the purpose of illustrating the concept of soundscape planning, energetic masking has therefore not further been taken into account here.

Need for a metric

To be able to quantify overlap between marine mammal vocalizations and hydroacoustic signals, a next useful step would be to develop a metric for overlap. Erbe (2015); Erbe et al. (2016) introduced the maskogram, a model with which the extent of a zone of masking around a sound source, including masking release mechanisms (*e.g.*, spatial release), can be visualized. Such a tool would be useful to better understand and potentially quantify whether signal overlap also results in actual masking of signals for marine mammals. Nevertheless, Erbe's maskograms rest on elaborative behavioral experiments to determine auditory detection thresholds under varying noise conditions, which to date only have been conducted with very few marine mammal species and test signals (Ketten, 2004; Erbe, 2015). The complexity of auditory processes related to masking in marine mammals in combination with how little is known on the auditory sensitivity of marine mammals on a species level therefore does not allow "measuring" acoustic overlap in terms of auditory masking.

Jain et al. (2014) developed a model incorporating signal structures as well as spacing information on signalers and receivers to estimate temporal, spectral and active space overlap in insect multispecies acoustic assemblages. A similar approach could be applied to marine mammal acoustic assemblages to test how the acoustic overlap changes when a human-generated sound source is added and how parameters can be tuned to minimize such overlaps. In the model by Jain et al. (2014), positional information and sound pressure levels (SPLs) of simultaneously calling katydid and cricket species were used to gauge the individual active space (defined as the area with the calling individual in the center and radius defined by a given assumed receiver hearing threshold). Information on species' active space was used to determine the "effectiveness" of acoustic overlap, *i.e.*, the extent to which active communication spaces overlapped between simultaneously calling species. In the case of soundscape planning, this would be the ideal measure to quantify how relevant overlap between biotic and man-made signals is. The equivalent type of information (*i.e.*, instant positional and SPL information of callers) necessary to determine active communication space for marine mammals would nevertheless have to be collected *in-situ*, which is logistically not realistic in the majority of cases.

Nevertheless, temporal, spectral and signal structure related overlap, which has also been shown to drive partitioning in multi-species acoustic assemblages (Amézquita et al., 2011; Planqué and Slabbekoorn, 2008; Jones and Siemers, 2011; Schmidt et al., 2013), can readily be quantified from acoustic records and may therefore provide a useful metric to quantify and compare levels of acoustic overlap between hydroacoustic instrumentation and marine mammals.

Effective temporal overlap

Gross-scale temporal overlap may occur at different scales. Species may call in different seasons (seasonal; *e.g.*, Van Opzeeland and Miksis-Olds, 2012), different times of day (diel; *e.g.*, Ruppé et al., 2015), or even call during the same time of day, but avoid calling together by interspecific acoustic inhibition (*e.g.*, Greenfield, 1988; Paez et al., 1993; Brumm, 2006). Finally, signal structure, such as amplitude or frequency modulation of calls, may further aid to overcome overlap between simultaneously calling species (*e.g.*, millisecond time scale; Jain et al., 2014). To determine the extent at which temporal overlap occurs within assemblages, but most importantly between assemblages and hydroacoustic sound sources, good knowledge or a model of the temporal structures of animal calls and the duty cycles of hydroacoustic sound sources is a prerequisite to then determine the *probability* of overlap, *e.g.*, by using the method developed by Masco et al. (2016). In our study, the SBDs functioned as a first conceptional visualization tool. However, in contrast to an actual LTS, these SBDs do not take into account fluctuations in acoustic activity within periods of acoustic presence, and (in our case) are based on daily acoustic presence/absence information from manual analyses. Marine mammal calls are not homogenously distributed over time. Information on temporal scales over which call activity fluctuates, down to the temporal structures of the calls themselves, will be key to quantify the effectiveness of temporal overlap between sounds of biotic and human origin from their probability of overlap.

To reduce analysis effort and move away from manual processing as has been done in the current study to obtain the SBDs, evaluating the energy contribution in species-specific frequency bands could provide a fairly quick first measure of how the acoustic energy of a given species is distributed over varying time scales (*e.g.*, Menze et al., 2017).

Spectral overlap

To determine the extent of spectral overlap between marine mammal species and hydroacoustic signals, the power spectra of representative calls of the respective species can be compared and overlap quantified, as has been done illustratively here for the RAFOS signal and leopard seal calls. In the current SBDs, no differentiation was made with regard to the energy contribution within species-specific frequency bands. For most species this is an oversimplification given that most energy is contained in specific sub-bands occurring within the species-specific frequency band. Figure 8 for example, shows a spectrograms of calls produced by leopard seals with most of the acoustic activity occurring in the 200–400 Hz band and some in the 2,000–4,400 Hz band, whereas the full 200–4,400 Hz band is used for the SBDs. Including more detail in the SBDs and combining them with information from spectral analyses will provide a more detailed picture of the interaction between sources and potentially vacant niches.

Open questions

Even if the soundscape planning concept does not depend immediately on the more general aspects related to soundscapes and acoustic assemblages addressed below, mentioning these here is nevertheless of relevance to place the concept in its larger biological context.

Fundamental acoustic niche assumption

The marine soundscape planning concept bases on the fundamental assumption underlying the acoustic niche hypothesis that sound-producing species benefit from partitioning the acoustic environment. As briefly mentioned in the introduction, studies into acoustic niche formation have however, also produced some contrasting results (see Helfer and Osiejuk, 2015 for an overview). Tobias et al. (2014) and Helfer and Osiejuk (2015) both question the fundamental assumption that species in acoustic assemblages are likely to systematically acoustically diverge to minimize interference and argue that opposing hypotheses *e.g.*, that species benefit from acoustic synchrony in order to function as extended multi-species communication networks has rarely been tested (Tobias et al., 2014). Lack of acoustic partitioning, such as for example identified in multi-species insect acoustic assemblages by Diwakar and Balakrishnan (2007), Cardoso and Price (2010) and Tobias et al. (2014), has, for example, been suggested to be explained by other selective forces, such as adaptive interspecific communication or predation, exerting stronger pressures than competition for signal space. Furthermore, selection on the receiver side, may lead to fine-tuning of the recognition mechanisms without driving divergence of the signals themselves (Seddon and Tobias, 2010). Also, the overall acoustic background against which species produce sound, may also dominate the timing of acoustic windows that are better than others suited for acoustic signaling (*e.g.*, Waser and Brown, 1984; Lengagne and Slater, 2002).

In the context of the marine soundscape planning concept, we emphasize that for the application of the acoustic niche principle to deployment planning for hydroacoustic instrumentation, this discussion is irrelevant. Whether certain marine mammal species deliberately cluster their vocal activity or partition the acoustic environment, the concept of soundscape planning honors the importance of considering the acoustic environment as a holistic entity that has been shaped by the various processes that make up and drive its ecology. The introduction of human-made sound has the potential to impact on these interactions that have evolved into mutual acoustic co-existence in a given acoustic environment (Dumyahn and Pijanowski, 2011). Hence, evaluation of the repercussions of introducing anthropogenic sound into the marine environment should also be based on an understanding of the dynamics of the acoustic community inhabiting the areas where sound is introduced and exploit the available acoustic windows that the assemblage leaves unoccupied. Finally, when considering soundscapes as a whole, we note that there is likely also a benefit when these also entail some unfilled acoustic space offering room for *e.g.*, acoustic divergence and cultural mutations in vocal behaviour (*e.g.*, Wilkins et al., 2013).

Functional acoustic assemblages

One of the questions that warrant further investigation for underwater habitats is whether local multi-species acoustic assemblages also represent actual functioning (*i.e.*, interacting) acoustic communities. Given that water is an excellent transmission medium for acoustic signals and sound can travel long distances underwater, acoustic assemblages in the underwater marine realm recorded at a given location will in most cases be composed of both local and more distant contributors. The "border" or acoustic horizon of each contributor's acoustic environment will be determined by the species-specific vocal behavior and hearing capabilities. The horizons of the acoustic environments that each contributor perceives will be determined by the species-specific vocal behavior and hearing capabilities. For example, the presence of long-range Antarctic blue whale calls in the coastal Antarctic recording location does not necessarily mean that a distant Antarctic blue whale perceives Weddell seal (*Leptonychotes weddellii*) calls, although both form part of the coastal acoustic environment. In analogy, the local presence of hydroacoustic sound sources does therefore not necessarily equally impact all vocally active species with which it overlaps in the SBD. Information on the actual active space of callers would be highly informative on which contributors can actually be assumed to belong to the assemblage and which can be considered part of the local ambient acoustic environment. However, as discussed previously, the current data status on marine mammal hearing prohibits building representative models of marine mammal active communication spaces within multi-species acoustic assemblages.

Soundscape orientation

The marine soundscape planning concept does not take into account how hydroacoustic signals may interfere with an animal's passive use of sounds from the acoustic environment (Farina, 2016). Soundscape orientation involves the use of specific sounds as cues for general orientation (including predator avoidance and prey finding) within a landscape (sound marks; Slabbekoorn and Bouton, 2008). Environmental sounds that are used for orientation and information purposes may stem from conspecifics, heterospecifics, or abiotic sources (*e.g.*, ocean surf, ice-related sounds). Environmental sounds are thought to provide important guidance during movement, particularly in underwater environments where the availability of visual cues is often low. For most instrumentation types, the overlap is likely to be largely released by the intermittent nature of the signals (*e.g.*, RAFOS, tomographic sound sources, Table 1), allowing animals to perceive the full acoustic environment in between the signal intervals. However, in the case of seismic exploration, the temporal density and broadband nature of the signals has the potential to temporally block perception of soundscape-typical sound marks.

Outlook

As to furthering the concept of soundscape planning, we have emphasized the need for development of a metric to somehow quantify acoustic overlap. Furthermore, the terrestrial realm could provide a suitable environment for first trials on how animals respond in a soundscape planning experiment by investigating if animals respond differently to signals depending on how the timing and characteristics are chosen to avoid overlap with the conspecific communication channel. The terrestrial environment has the advantage that behavioral observations are conducted more easily compared to the underwater environment. Furthermore, experiments could be carried out with (bird) species with well-known auditory characteristics to better understand the role of active acoustic space in the context of overlap avoidance.

Finally, the acoustic environment (both in the marine and terrestrial realm) should be regarded as a limited and vulnerable natural resource that has to be managed with the intent of rational utilization, protection and quality enhancement where appropriate (Dumyahn and Pijanowski, 2011). Although the soundscape planning concept may provide a solution to reduce mutual interference between marine mammal and intentional anthropogenic acoustic signals, the bulk of anthropogenic underwater noise stems from unintentionally produced anthropogenic signals, such as caused by ship traffic and construction. Addressing this issue is imperative, but beyond the scope of this study. The soundscape planning concept, although still in its nonage, has in our opinion the potential to contribute raising the awareness, at least in the scientific community applying hydroacoustic instrumentation, that introducing sound in natural acoustic environments can have consequences for the local acoustic assemblage. For the benefit of the quality of the hydroacoustic data collected, the acoustic conditions of the target area may be considered as equally important as any other site characteristic crucial for decisions on timing and position of the experiment. This may render exploration of site-relevant passive acoustic data for the possibility to apply pre-deployment soundscape planning a desirable standard preparatory practice in the (near) future.

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Competing interests

Ilse Van Opzeeland and Olaf Boebel declare that they have no conflict of interest.

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