Aquatic Mammals 2019, *45*(6), 576-611, DOI 10.1578/AM.45.6.2019.576

An Overview of Potential Impacts of Hydrocarbon Exploration and Production on Marine Mammals and Associated Monitoring and Mitigation Measures

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Abstract

Offshore hydrocarbon exploration and production (E&P) activities can overlap in space and time with marine mammal populations. These activities, especially seismic surveys, can generate loud sound levels that propagate well in the marine environment. Exposure of marine mammals at varying distances from the source of these sounds can result in a range of different impacts, from auditory injury to behavioral responses and masking. The source-pathway-receiver (SPR) model is a framework often used in environmental impact assessments. In this overview, the SPR model is applied to summarize the current understanding of (1) E&P impulsive sound sources such as airgun arrays and continuous sounds originating from drilling (source), (2) the propagation of sound generated by these sources through the ocean's water column (pathway), and (3) the impacts of these sounds on marine mammals (receiver). Potential unmitigated impacts of E&P activities on marine mammals can be categorized according to their impact severity and spatial scale, ranging from severe impacts occurring at a small spatial scale to lower level impacts occurring at larger scales (typically, but not always, in the following order: permanent auditory threshold shift – temporary auditory threshold shift – behavioral disturbance – masking). Available monitoring techniques, applied to enhance our understanding of marine mammals as related to the potential full range of E&P impacts from individual behavioral responses up to population-level consequences, are also described using the SPR model. Additionally, the range of mitigation measures applied in the E&P industry to prevent unacceptable impacts to marine mammals are provided and categorized according to a mitigation hierarchy (avoid > minimize > restore > offset). Finally, a case is made for application of the ALARP (As Low As Reasonably Practical) principle in seismic mitigation guidelines—that is, the applied mitigation measures in specific E&P activities should be proportional with the assessed risk on marine mammal populations, as well as reasonably practicable to achieve.

Key Words: seismic surveys, drilling, impacts, monitoring, mitigation hierarchy, marine mammals, exploration and production

Introduction

Offshore hydrocarbon exploration activities, specifically seismic surveys, are often associated with the generation of loud sound levels that propagate well in marine environments. These activities can overlap in space and time with marine mammal populations in different stages of their life cycle—that is, during migration or at their feeding and breeding grounds. Exposure to both loud continuous or impulsive marine sounds can potentially have several types of impacts on marine mammals. These can be classified into different categories such as mortality, injury to the hearing system (Permanent Threshold Shift [PTS]), temporary reduced hearing sensitivity (Temporary Threshold Shift [TTS]), behavioural disturbance, and communication masking. When unmitigated, sound levels generated by some sound sources, such as sonar, can have lethal effects on cetaceans (Simmonds & Lopez-Jurado, 1991; D'Amico et al., 2009). Although inferences have been made that seismic surveys can cause mortality, to date, there is no conclusive evidence supporting a connection between marine mammal mortality and seismic surveys. Exposure of marine mammals to airguns at close range or for a prolonged period, however, has the potential to result in damage at the cellular level of the hearing system, commonly referred to as *injury* (PTS), or a shift in hearing sensitivity measured in decibels (dBs) referred to as *TTS*, also known as auditory fatigue (Southall et al., 2007, 2019; Finneran, 2016). Additionally, monitoring studies of various species of marine mammals indicate that animals can respond to sound generated by seismic surveys, drilling, or the presence of industry vessels in manners that include head turning to regulate exposure levels, movement away from the sound, or temporary cessation of behaviors such as feeding or swimming (Nowacek et al., 2007; Southall et al., 2007; Ellison et al., 2011). Another example of potential behavioral effects of sound are impacts to communication between conspecifics as marine sound has been observed to influence the number of vocalizations in baleen whales (Di Iorio & Clark, 2010; Blackwell et al., 2013, 2015; Cerchio et al., 2014). Marine sounds generated by the Exploration and Production (E&P) industry also have the theoretical ability to mask vocalizations used for navigation, communication, or prey localization (Southall et al., 2007; Sills et al., 2017), although masking demonstration is very difficult—in part, because animals possess many adaptations to reduce the likelihood of a sound of interest being masked (Erbe et al., 2016).

The source-pathway-receiver (SPR) model is often used in environmental impact assessments (Cerrato & Goodes, 2011). This overview uses this model as a framework to describe sound sources used in the E&P industry (source), how sound generated by these sources propagates through the ocean over various distances (pathway), and, ultimately, how sound can impact marine mammal individuals and populations (receiver).

Whereas some of these impacts are reasonably well understood because they have been the subject of numerous studies and monitoring programs, such as certain hearing studies using airguns (Finneran et al., 2015; Reichmuth et al., 2016; Kastelein et al., 2017; Southall et al., 2019), there are significant knowledge gaps associated with others (e.g., masking; Erbe et al., 2016). For this reason, key knowledge gaps are being filled through various research programs, with funding provided by national regulatory agencies, the E&P industry, nongovernmental organizations, research institutes, or other entities (e.g., Bröker et al., 2018). Studies are conducted both in laboratory settings and in the natural environment. Additionally, during exploration projects such as seismic surveys, monitoring programs are sometimes implemented to enhance our understanding of marine mammal responses and to determine the efficacy of applied mitigation measures (Malme et al., 1986, 1988; Yazvenko et al., 2007; Bröker et al., 2015; Martin et al., 2017, 2019; Austin et al., 2018). A range of different monitoring techniques and technologies that can be applied during E&P activities are summarized in this overview. Monitoring programs often focus on population-level effects, such as changes in distribution and abundance (Muir et al., 2016), or on individual-level effects, such as changes in swimming, breathing, or diving behavior (Gailey et al., 2016). Over the past several years, extensive progress has been made in the quantification of the link between behavioral changes on an individual level and the possible consequences at a population level (Villegas-Amtmann et al., 2015, 2017; Costa et al., 2016).

Through monitoring programs and behavioral response studies, significant progress has been made towards enhancing our understanding of impacts of seismic sound on marine life and which mitigation measures can be used for monitoring and mitigation to avoid or reduce these impacts (Nowacek et al., 2013; National Marine Fisheries Service [NMFS], 2016; Joint Nature Conservation Committee [JNCC], 2017). Avoidance of impacts can be achieved by planning to circumvent spatial and temporal overlap between E&P activities and presence of marine mammal populations, especially during the biologically important life stages such as the breeding and feeding seasons. Some examples of mitigation measures to avoid and/or reduce impacts are to use the lowest possible source levels, reduce sound levels generated by E&P vessels and equipment, and eliminate unnecessary high frequencies, ramp-up, and use of exclusion zones, including shutdowns (all further described in the "Mitigation" section).

Concern over the impact of E&P sounds on marine mammals became more predominant in the 1980s (Malme et al., 1984, 1986, 1988). Richardson et al. (1995) presented a comprehensive overview of the impacts of all types of marine sound on marine mammals. Since then, further reviews on sound impacts on marine mammals have been developed (Evans & Nice, 1996; Richardson & Würsig, 1997; Gausland, 2000; Gordon et al., 2004; Nowacek et al., 2007; Southall et al., 2007, 2019; Weilgart, 2007). This overview builds on those earlier reviews and provides a summary of the relevant knowledge gained over the past decade, providing an up-to-date description of (1) key sound sources used in the E&P industry, (2) propagation of sound in the marine environment, (3) types of impacts that E&P activities can have on marine mammals, (4) the different monitoring methods that are implemented to enhance our understanding of E&P impacts, (5) the mitigation measures currently applied in the E&P industry using the mitigation hierarchy, (6) a brief summary of international guidelines, and (7) recommendations for future studies. There is a wealth of knowledge on impacts of sonar and other sound sources on marine mammals and other forms of marine life, but this has not been included. The focus of this overview is solely on E&P activities and their impacts on marine mammals.

Characterization of Sound

Sound is typically parsed into two components: (1) pressure and (2) particle motion (Stewart, 1932; Popper et al., 2014). Sound pressure in water is the variation in hydrostatic pressure caused by the compression and rarefaction of particles as the sound wave propagates. Particle motion is the oscillatory back- and forward movement of particles, which then moves the particles adjacent to them. Particle motion can be expressed as displacement (m), velocity (m s^{-1}), or acceleration (m s^{-2}) (Popper et al., 2014; Slabbekoorn et al., 2019). Whereas most fish and invertebrates primarily rely on particle motion to sense sound (Popper et al., 2003), it is of less importance to marine mammals as evolution of the mammalian ear operating in air has led to a greater dependence on pressure for hearing sound (Finneran et al., 2002). As the focus of this overview is on marine mammals, particle motion is not further addressed in this summary.

The primary metrics used to characterize sound are (1) duration (expressed in seconds [s]), (2) frequency (expressed in Hz), and (3) amplitude frequency (measured in pascals [Pa]). Several metrics are used to describe different aspects of the amplitude of a sound with common ones being sound pressure level (SPL) expressed in dB re 1 µPa and sound exposure level (SEL) expressed in dB re 1 μPa^2. Other less common but still relevant metrics are rise-time, kurtosis, signal to background noise, or sound level above hearing threshold (Ellison et al., 2011).

The *duration* of a sound is dependent on the type of source and activity generating the sound. A differentiation is made between *continuous sound*, which has no well-defined start and end, such as sound generated in a busy shipping lane, and *impulsive sound*, which has a clear start and end, such as the primary seismic pulses that typically last several milliseconds and are repeated every 10 to 15 s. It is a relevant parameter in a biological context as it influences sound exposure metrics such as SEL or equivalent continuous sound level (Leq) that are used to determine when injury can occur to the hearing system of marine mammals. Effective duration is treated differently for continuous and pulsed sound. For this reason, sound threshold levels associated with the onset of auditory injury or behavioral responses can be different for the two types of sound with respect to duration.

The *frequency* of a continuous sound signal is the number of pressure wave cycles per second (expressed in Hz) and is relevant for two reasons. First, propagation of sound through a marine environment is frequency dependent. In deeper waters, lower frequencies propagate farther due to lower attenuation, which is the loss of sound in the water column caused by absorption, scattering, and leakage out of sound channels (Urick, 1983). Second, marine mammals' perception of sound can be classified into different functional hearing groups, the species in each group having optimum hearing in different frequency bands. Cetacean species are broadly divided into low-, medium-, and high-frequency hearing groups for convenience in predicting the likely hearing spectrum of a given species, even if its audiogram has never been tested directly (Southall et al., 2007; NMFS, 2016, 2018). This is considered reasonable given the inherent evolutionary conservatism we see in auditory anatomy and function, consistent with the importance of hearing to an individual's survival and reproduction (Southall et al., 2007, 2019; NMFS, 2016, 2018). Southall et al. (2019) uses a different classification and makes the distinction between low (LF), high (HF), and very high (VHF) frequency species. The generalized hearing frequency ranges for cetaceans put forward by the U.S. National Marine Fisheries Services (2016) are 7 Hz to 35 kHz, 150 Hz to 160 kHz, and 275 Hz to 160 kHz for low-, medium-, and high-frequency hearing groups, respectively. Pinnipeds' hearing ranges are distinguished for animals in air and in water, with the estimated auditory bandwidths for the latter set at 60 Hz to 39 kHz for sea lions and fur seals (otariids) and 50 Hz to 86 kHz for true seals (phocids) (NMFS, 2016, 2018).

The *amplitude* is the extent of variation of the sound pressure. The acoustic energy of a sound wave is proportional to the square of its amplitude. The SPL of a sound is given by SPL = 20 log (P/P_0), with P being the pressure amplitude and P_0 being a reference pressure level. SPL is expressed as a relative measure (i.e., referenced to a pressure P_0 of 1 micropascal [µPa] in water and 20 µPa in air; Urick, 1983; Richardson et al., 1995). This difference in reference between the two media is one of the reasons why SPLs in air and in water are not directly comparable. Acoustic levels such as SPL are expressed in dBs, a unit that has been used historically for calculating acoustic quantities. Due to the logarithmic scale, the dB offers a convenient way of handling large ranges of values such as can be the case with sound levels (Urick, 1983). Relevant metrics of SPL are (1) SPL – the average sound pressure level over a defined period, often 1 s for a continuous sound or 90%

of the duration of an airgun pulse based on accumulation of energy from 5 to 95% (Thode et al., 2010; Martin et al., 2017); (2) SPL_{pk} or peak pressure level – the maximum instantaneous sound pressure in absolute value; and (3) $SPL_{pk\text{-}pk}$ or pressure level peak to peak – the difference between the maximum positive and maximum negative instantaneous sound pressure. Another relevant metric, including for cumulative and aggregate sounds from multiple sources, is the SEL, which is a measure of energy in a signal of a certain duration. This is the time integral over the duration of the exposure of the instantaneous pressure squared with the unit dB re 1 $\mu Pa^2 s$ in water (Southall et al., 2007; American National Standards Institute [ANSI], 2013; Finneran, 2015). Whereas SEL is usually referred to as the sound energy over 1 s for continuous sound or over a single pulse (i.e., typically < 1 s) for airguns or other pulsed sources, the time frame over which cumulative sound exposure level (cSEL) is estimated can range from a few minutes or hours of one activity, such as a single seismic survey transect, to a full 24-h accumulation of all sound energy from multiple activities. Although 24 h is a rather arbitrary choice without clear biological significance, it is used in recently promulgated guidelines (e.g., NMFS, 2016, 2018) as the prescribed period for cSEL estimation in threshold criteria for the onset of auditory injury. A few reasons why the 24-h period lacks biological significance include (1) animals are not stationary, and exposure to anthropogenic sound rarely continues for 24 h due to animal movement as well as source movement for non-stationary sources; (2) possible periods of silence within the 24-h period are not considered, during which recovery of the hearing system occurs; and (3) due to the logarithmic scale of sound propagation, it is mainly the closest distance between the source and animal that contributes to the total SEL, which usually occurs in much shorter periods than 24 h (Martin et al., 2019).

Sound levels from a vessel or an industrial activity are commonly reported as *source levels* (SLs), typically referenced to 1 m from the source (measurements generally taken at a distance of tens to hundreds of meters in the far-field—that is, the area where the sound field appears to emanate from a single point—and estimated at 1 m range through numerical “back propagation”) for consistency and ease of comparison between sources. By contrast, the reporting of *received levels*, which are sound levels at a receiver arbitrarily located, such as a marine mammal (Southall et al., 2007), must specify the range between source and receiver to provide some sense of the potential dispersion or attenuation of sound energy that has occurred over the propagation distance.

Finally, although there is no scientific basis for making a distinction between sound and noise, they are not entirely equivalent concepts. Whereas sound is a quantity that can be objectively quantified, noise is a subjective label that depends on the perception and viewpoint of sound by a receiver.

Source-Pathway-Receiver Model

Source

Several different acoustic sources are used by the E&P industry to image the sea bottom and the subsurface, sometimes up to 10 km deep. Examples are airgun arrays, multi-beam echo sounders, sub-bottom profilers, side scan sonar, sparkers, and boomers, which all target different subsurface depths by using different SLs, frequencies, and beam-widths. For example, multibeam echo sounders are used to map the seabed and use frequencies in the range of ~12 to 500 kHz, sub-bottom profilers target the first several hundred meters of depth below the sea floor and use frequencies in the range of 2 to 24 kHz, and seismic airgun arrays target much deeper structures (up to 10 km) and mainly use low-frequency energy (~< 300 Hz) (Richardson et al., 1995; MacGillivray et al., 2014). Whereas these sound sources can be loud, they have a direct purpose—to penetrate the subsurface to measure the earth’s (geo-) properties which are used to determine the potential presence of hydrocarbon deposits. Several other offshore E&P activities generate sounds without such a purpose, with examples including shipping (e.g., liquid natural gas [LNG] and oil tankers), dynamic positioning (DP) systems (as used in deep water drill rigs), and drilling. Thus, a key distinction between different E&P sound sources is that some are used as a sensor or communication device and others are a byproduct of mechanical/propulsion systems. This has consequences for the potential applied mitigation measures as avoidance of needed E&P sound sources is typically not possible and a reduction in SLs could be problematic as it could likely result in sub-optimal data quality. On the contrary, elimination or a reduction of sound generated by an activity as byproduct (i.e., noise) does not affect the effectiveness of that activity. A comprehensive summary of underwater sounds produced by the E&P industry is provided in Jiménez-Arranz et al. (2017).

Airguns—Compared to other E&P sound sources, impacts of airgun arrays on marine life have received the most attention due to concerns over the high amplitude and pulsed sound that are generated at regular intervals (10 to 15 s) (Caldwell & Dragoset, 2000). Seismic surveys are conducted for periods ranging from weeks to several months, depending on the area to be surveyed. An airgun array consists of several airguns, commonly arranged in a rectangular configuration. The planar array is oriented parallel to the sea surface, typically with the airguns simultaneously releasing high pressure air (usually around 2,000 psi, equivalent to 13.8 MPa) into the surrounding water (Amundsen & Landrø, 2010). The air pressure and vent size generate an expanding bubble that creates an initial pressure pulse of very short durations (0.004 to 0.005 s) (Caldwell & Dragoset, 2000; Gisiner, 2016). These arrays are typically towed at depths of 3 to 10 m below the water surface at speeds of around 5 kts (2.5 m/s). The high-pressurized air coalesces into a bubble, which generates sound by the ensuing expansion and contraction of the oscillating bubble (Johnson, 1994). The arrays are designed so that the different bubble interactions result in a downward directed, high-amplitude, primarily low-frequency sound pulse that can penetrate the subsurface to depths of several kilometers. Sound propagating through the subsurface is reflected and refracted by the different types of rock layers. Stationary receivers at the sea bottom (nodes) or towed at the sea surface (streamers) record the sound returned from the underlying geology, which is then used to build a two-dimensional (2-D) or three-dimensional (3-D) image of the subsurface geology (Long et al., 2006; Gisiner, 2016). This technique significantly increases the rate of success when targeting hydrocarbon reservoir drilling activities. Whereas airgun arrays are designed to be directional (i.e., the loudest sound levels are aimed towards the bottom), there is substantial sound energy propagating into the horizontal plane as well (Caldwell & Dragoset, 2000). Sound levels emitted horizontally are about 20 dB lower than those emitted vertically, with intermediate values observed at intermediate angles (Caldwell & Dragoset, 2000). The pattern of radiated sound is also frequency dependent as the pulses from multiple airguns interact and interfere with each other (MacGillivray, 2006).

The sound levels of airgun arrays (i.e., the SL) depend on the air pressure, the number of individual airguns, and the sum of the volume of each individual airgun in the array. With pressure typically being fixed at 2,000 psi, the number of individual airguns and the total volume of the array is varied, depending on the depth of the geological strata of interest and the material composition of the geological layers (e.g., basalt and salt layers are acoustically dense and require more energy to penetrate). Airgun arrays typically range in total volume from 500 to 5,000 in^3, although arrays up to 8,000 in^3 are occasionally used and are usually comprised of 12 to 48 individual guns with air reservoir volumes in the range of 10 to 500 in^3 each. SLs from individual airguns range from 200 to 232 dB re1 µPa @ 1 m for small to large individual airguns, respectively (Richardson et al., 1995; Hermannsen et al., 2015; Jimenez-Arranz et al., 2017). Array SLs range from 235 dB re1 µPa @ 1 m for a small array (500 in^3) to 260 dB re 1 µPa @ 1 m for large arrays (7,900 in^3). Note that these nominal SLs at 1 m do not exist anywhere in, or near, the physical framework of an array that is a distributed source typically up to 20 m in length and width (e.g., 16 × 16 m). Instead, these are values derived by back-propagating levels measured in the far-field. As mentioned previously, SL specifications of airgun arrays refer to sound levels in the vertical direction, with nominal sound levels in the horizontal plane being approximately 10 to 20 dB lower (Caldwell & Dragoset, 2000). Most of the generated sound is below 250 Hz, with 90% of the energy between 70 to 140 Hz (Tolstoy et al., 2004; Jimenez-Arranz et al., 2017). However, pulses do contain some higher frequencies, at least up to 16 kHz, albeit of low energy levels (Madsen et al., 2006; Tyack, 2009; Hermannsen et al., 2015; Martin et al., 2017).

Drilling—Whereas sound used for imaging of the ocean bottom and the subsurface geology has a specific objective, sound generated from drilling is a byproduct of the mechanical vibration of the rock and drill bit and is therefore considered noise. Some key differences between airguns and drilling activities in sound levels are (1) lower SPLs than those observed with airguns, (2) drilling is continuous rather than impulsive as with airguns, and (3) drilling levels contain relatively less low-frequency energy (Austin et al., 2018). Due to the continuous nature of drilling activities, the total sound energy animals can be exposed to can exceed regulatory thresholds (expressed in SEL) set to minimize impacts to marine mammals (Southall et al., 2007, 2019; NMFS, 2016, 2018). Drilling activities produce different types of sound: (1) sound generated by the rotating drill bit on the substrate, which is often tonal in nature; (2) sound of cavitation caused by the dynamic positioning thrusters used to keep the drill rig stationary, which is used in deeper waters where anchoring to the sea bottom is not feasible; (3) noise generated by support vessels; and (4) noise from equipment and machinery used on the rig such as pumps, generators, engines, hydraulic winches, cranes, etc., which are transmitted into the water column through the hull or gravity-based structure. Details on measurement of drilling activity sound levels are mostly presented in industry and government reports, impact assessments, and permit applications (e.g., Greene, 1987; Bureau of Ocean Energy Management [BOEM], 2015). Peer-reviewed literature on this topic is scarce.

Austin et al. (2018) reported on measurements taken during drilling activities of three different moored drill vessels in the Arctic Chukchi and Beaufort Seas. These activities included drilling of a mudline cellar in the upper sediment (6 to 7 m in diameter and 11 to 12 m depth). Mudline cellars are constructed to house the wellhead and blow-out preventer to mitigate risks associated with potential scouring of the seabed by ice in shallow waters. Acoustic measurements taken during drilling indicated the presence of several tones, with dominant frequencies and harmonics below 2 kHz and higher harmonics present to 10 kHz. Power generating equipment, engines, pumps, and rotating equipment resulted in tones below 100 Hz. Broadband drilling source levels for these three vessels ranged from 169 and 175 dB re 1 µPa @ 1 m. Sounds generated by mudline cellar excavation were more broadband in nature and had higher SLs, ranging between 192 and 193 dB re 1 µPa @ 1 m. A drilling sound source verification program was conducted by MacDonnell (2017) during a drilling program using the drilling vessel *Stena IceMAX* in 2,000 m of water. This vessel was held in position with dynamic positioning (DP) thrusters. Recordings taken at 2 km from the drilling activities indicated that the DP thrusters masked most of the sound generated by the drilling itself. Thruster noise energy was dominant in the 50 to 1,000 Hz band, with average SLs of 187 dB re 1 µPa @ 1 m. Drilling tones were detected at 14 Hz at average sound levels of 164 re 1 Hz µPa/Hz @ 1 m.

Source Modeling—Seismic source modeling is often conducted to estimate, before the physical device is deployed or even constructed, the specific output of an airgun array in terms of frequencies, directionality, ghost effect (sound reflection from the sea surface), and SLs. The output of these source models can then be fed into propagation models to determine sound levels and their spectral distribution at any range and direction from the source. Source models consider the configuration of an array in terms of the location, number, and volume of individual airguns; pressure, depth, and interaction between the oscillating bubbles released by individual airguns; and estimation of array output (SLs and frequencies) in the vertical plane (Laws et al., 1990; Tashmukhambetov et al., 2008; Goertz et al., 2013). Some models estimate in the horizontal plane as well (MacGillivray, 2006). Examples of seismic source models are Gundalf (Laws et al., 1990), Nucleus (Goertz et al., 2013), and JASCO's Airgun Array Source Model (AASM) (MacGillivray, 2006).

Propagation

Propagation Fundamentals—Sound travels in water five times faster than in air and with less loss of energy due to the greater density of water. Acoustic energy, therefore, propagates better in water than in air (Urick, 1983). Sound propagation in water is influenced by numerous factors such as the sound's frequency; variability with depth of water density, temperature, and salinity; surface and seafloor roughness; bathymetry; and geo-acoustic properties of the subsurface (Urick, 1983; Lurton, 2010; Wang et al., 2014). As sound propagates away from a source, it is subject to a diminution in sound level referred to as transmission loss (TL). In deeper water, and at ranges away from the source that are smaller compared to the water depth, sound from a point source spreads spherically with transmission loss approximated by $TL = 20\log_{10}[R]$, where R is the distance to the source in (kilo)meters (Urick, 1983). In shallow water (or in a sound channel), sound propagates like a cylindrical front, with energy loss constrained by the water surface and bottom, and with $TL = 10\log_{10}[R]$ (Urick, 1983). This means that under ideal propagation conditions, with every 10-fold increase in distance, sound levels generally reduce by 20 and 10 dB in deep and shallow water, respectively. Under most real-world conditions, the average loss of acoustic energy with distance is about 15 dB, commonly ranging anywhere from 12 to 17.5 dB with every 10-fold increase in distance, depending on specific local conditions and the frequency of the sound (Urick, 1983; Richardson et al., 1995; Medwin & Clay, 1998). Low-frequency sounds (10 to 500 Hz) are absorbed by seawater less than higher frequency sounds (Urick, 1983), and sounds below 100 to 200 Hz can travel distances of several hundreds, even thousands, of kilometers at depths of around 800 to 1,000 m due to the temperature-pressure profile of the water column that confines sound in a low-loss layer, referred to as the "Deep Sound Channel" or SOFAR (Sound Fixing and Ranging) channel (Urick, 1983; Munk et al., 1994; Medwin & Clay, 1998; Širovića et al., 2007). High and very high frequencies (>100 kHz) attenuate rapidly in marine environments, and propagation is usually limited to a few kilometers (Hildebrand, 2009).

Propagation Modeling—Propagation models are used to predict how sound travels through the marine environment and to estimate the level of sound at different distances away from the source. As a tool for assessment of potential impacts, propagation modeling can be applied to determine the radii of different impact zones (injury or behavior) around a sound source and to estimate potential exposure levels of marine mammal populations in critical areas that may be farther away—for example, on feeding or breeding grounds (Martin et al., 2017). Several different models are used depending on water depth, frequency of the sound, and distance from the source (Jensen et al., 1994; Lurton, 2010; Wang et al., 2014; Ainslie et al., 2016). The Ocean Acoustics Library (www.oalib.hlsresearch.com) provides various modeling packages of these different types of models as well as other useful resources.

Receiver

Exposure, vocalization, and auditory morphology studies have demonstrated that marine mammals have significant differences in their auditory capabilities (Wartzok & Ketten, 1999; Southall et al., 2007, 2019). Because of these differences, cetacean species are categorized as low-, mid-, and high-frequency hearing species. Mysticetes have their optimal hearing at low frequencies with an estimated auditory bandwidth between 7 Hz and 22 kHz (Erbe, 2002; Southall et al., 2007, 2019; Tubelli et al., 2012, 2018; Cranford & Krysl, 2015; Ketten et al., 2016; NMFS, 2016, 2018). Most odontocetes are grouped in the mid-frequency hearing range from 200 Hz to 180 kHz. Odontocetes specialized in high-frequency hearing (such as porpoises, the genera *Kogia* and *Cephalorhynchus*, and *Lagenorhynchus cruciger* and *L. australis*) have ranges of 275 Hz to 160 kHz. Due to their amphibious nature, pinnipeds are capable of both in-air and in-water hearing. Phocid pinnipeds (true seals) in water have a generalized hearing range of 50 Hz to 86 kHz. Otariid pinnipeds (sea lions and fur seals) in water have a hearing range of 60 Hz to 39 kHz. These generalized hearing ranges are composites based on audiograms of multiple species in their respective groups, resulting in broader ranges compared to the hearing range of an individual species (NMFS, 2016). Some studies suggest little variation in audiograms between species in the same phylogenetical group (Sills et al., 2015), likely due to its importance in survival and social contexts (and echolocation where appropriate). It is this lack of variation at a phylogenetic level that provides some confidence to extrapolate results from just a few tested species to the much greater number of related but untested species.

When discussing impacts such as injury, TTS, disturbance, or masking of a species, it is key to consider these species-specific hearing capabilities (Southall et al., 2007, 2019; Terhune, 2013; Tougaard et al., 2015; NMFS, 2016, 2018; Tougaard & Dähne, 2017) by means of frequency weighting. Frequency weighting is the correction for the frequency-dependent hearing abilities of different species, which helps us to understand how the animals are likely to perceive and use the sound that the physical description of the sound alone cannot provide. Frequency weighting originates from human audiology where different weighting filters are applied (e.g., A- and C-weighting). Southall et al. (2007) further advanced this concept with marine mammals in the form of M-weighing filters, which have been based on the audiograms obtained for several mid- and high-frequency species of marine mammals (and for in-air and in-water pinnipeds). Erbe et al. (2016) provide an overview of the marine mammal species whose audiograms have been recorded, which at the time of reporting, consists of 19 species of odontocetes, 13 species of pinnipeds, two species of sirenians, and the polar bear and sea otter. In contrast, no audiograms are available for mysticetes, and any weighting curve filter developed is largely based on results obtained from modeling of the mysticete hearing systems (Tubelli et al., 2012, 2018; Yamato et al., 2012; Cranford & Krysl, 2015). When discussing auditory impacts, such as injury, behavior, or masking as a function of sound exposure, it is important to note if unweighted or weighted sound levels are being used. The importance of frequency weighting has been established through TTS studies and is increasingly adopted in regulations and guidelines (NMFS, 2016, 2018; Southall et al., 2019). The relevance of frequency weighting for assessing and predicting behavioral responses and masking is starting to be recognized and requires further research (Tougaard et al., 2015; Tougaard & Dähne, 2017; Kastelein et al., 2019a). When assessing the number of individuals that may be exposed to anthropogenic sound levels that could cause injury or disturbance, acoustic thresholds are applied resulting in exposure zones around the source. The marine mammal distributions used to derive the number of exposed—or taken—animals within these zones are often considered as static—that is, the distribution is considered independent of the exposure levels. An alternative methodology is the application of "animats," where marine mammal distribution is assumed to be dynamic and dependent on the received sound levels. In these animat models, individuals' behavior, such as aversion, dive patterns, swim speeds, etc., is programmed to be dependent on sound levels received by those individuals. Although the behavioral dose-response curves are not always well known, use of this dynamic method can provide a more robust framework for assessing risk compared to the static method (Schecklman et al., 2011; Ellison et al., 2016; Frankel et al., 2016; Zeddies et al., 2017).

Impact Hierarchy

The potential impacts of E&P sounds on marine mammal individuals can, in general, be categorized by decreasing severity: mortality, injury, TTS, behavioural disturbance, and communication masking. With decreasing received sound levels and impact severity, the concentric regions around a sound source where these impacts occur increase in area (Figure 1). For example, injury to marine mammal hearing systems can only occur at high received sound levels, occurring up to several tens or hundreds of meters from an airgun array; whereas behavioral responses and masking can occur at much lower received sound levels and, thus, in larger areas (Richardson et al., 1995; Ellison et al., 2011; Cato et al., 2013; Hermannsen et al., 2015). The zones around a source in which impacts can occur are assumed to be 2-D and are typically not circular in shape due to, for example, source directionality, sound propagation conditions, and exposure duration. There are exceptions to the order of these zones. For example, TTS could occur in zones that are larger compared to zones in which behavioral responses happen. This impact hierarchy describes impacts to individual animals, which is not the same as population-level impacts. Behavioral responses occur at larger spatial scales and have a lower severity compared to injury, for example, but if many individuals are disturbed for a prolonged period of time, the population-level effects of disturbance are likely to be of more significance than the auditory injury observed in only a few individuals.

Mortality

Anthropogenic sound can result in mortality of marine mammals as has been witnessed in mass stranding events of beaked whales caused by use of navy sonar in the 2.6 to 14 kHz range (Cox et al., 2006; D'Amico et al., 2009). To date, there has been no evidence for a causal effect of marine mammal mortality as a result of hydrocarbon E&P activities such as seismic surveys or drilling activities. There have been some mortality events near seismic surveys, but these were not attributed to the seismic activity (e.g., Malakoff, 2002). One other inconclusive incident occurred where approximately 75 melonheaded whales (*Peponocephala electra*) succumbed due to multiple secondary factors (e.g., dehydration, sun exposure, etc.) after entering a shallow tidal estuarine system in Madagascar in 2008 (Southall et al., 2013). This uncommon behavior overlapped with a survey vessel using high-powered 12-kHz multi-beam echo sounding (MBES) equipment. An independent scientific panel of the International Whaling Commission, tasked with reviewing this incident, concluded that the exact cause of this stranding could not be determined, but that MBES could not be excluded as a cause (Southall et al., 2013). One issue with determining a causal link between marine mammal mortality and seismic surveys, or other anthropogenic sources, is that it is very difficult to determine from stranded animals whether exposure to sound was the cause of death. Furthermore, it is challenging to assess whether stranded animals died from direct physiological or anatomical consequences

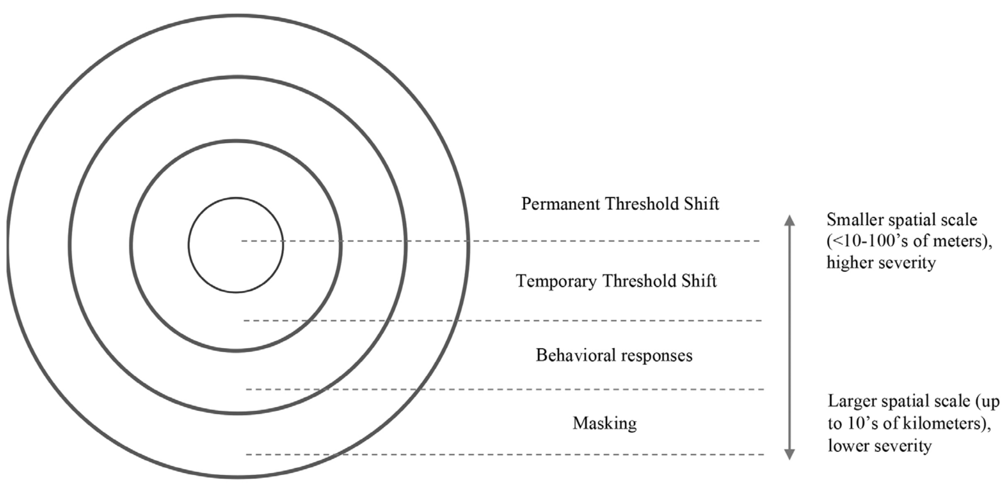

Figure 1. The impact hierarchy outlining the different impacts of E&P activities on marine mammal individuals, with a decrease in severity with increasing range of occurrence. Mortality has been omitted from this figure as no causal link between E&P sources and marine mammal mortality has been detected.

or indirectly from the consequences of behavioral responses or impacts on communication or navigation (MacLeod & D'Amico, 2006; D'Amico et al., 2009; Villegas-Amtmann et al., 2015, 2017). Although no direct causal relationship between use of airguns and marine mammal deaths has been identified so far, Heide-Jørgensen et al. (2013) expressed a concern about increased risk of ice entrapment by narwhal (*Monodon monoceros*) caused by seismic disturbance.

Permanent and Temporary Threshold Shifts

Impacts of loud sound on hearing systems are typically distinguished as PTS or TTS. TTS, also known as auditory fatigue, is a shift in hearing sensitivity measured in dBs (Southall et al., 2007). It typically occurs at the same frequencies of the exposure sound, although this is not always the case (Kastelein et al., 2017). The hearing systems of marine mammals are not different from that of humans in that the level of TTS depends on the level and duration of exposure, and the period over which recovery can occur ranges from minutes to days (Hirsh & Bilger, 1955; Charron & Botte, 1988). TTS is a reversible process and, in general, not considered an injury (Verboom & Kastelein, 2005; Southall et al., 2019). PTS, on the other hand, is non-recoverable and occurs after exposure to very loud and/or prolonged sounds (Southall et al., 2007, 2019; Finneran, 2015). The exposure level at which PTS is expected to occur, therefore, is often used as a criterion for injury determination (Southall et al., 2007, 2019; NMFS, 2016, 2018). This exposure level is based on applied extrapolation methods to predict 40 dB TTS (Southall et al., 2007, 2019), which is not presumed to be similar to the onset of injury as there are no available empirical data to test this assumption.

Based on inner-ear studies of animals accidentally exposed to loud sound sources, it is known that certain sounds cause damage at the subcellular level resulting in auditory injury (Bohne et al., 1985, 1986; Ketten et al., 1993). It has been shown that the cochlear hair cell and the synapse between the hair cell and the primary affected neurons can be lost after exposure, resulting in PTS (Ryan et al., 2016). Over the past decade, a significant number of controlled studies on the impact of various sound sources on marine mammal hearing have been conducted (Southall et al., 2007, 2019; NMFS, 2016, 2018). This is key research as it shapes evidence-based regulations required to minimize the risk of injury to marine mammals. Results of these studies are used to develop marine mammal exposure criteria (e.g., Southall et al., 2007, 2019; Tougaard et al., 2015; Finneran, 2016; NMFS, 2016, 2018). Studies are typically conducted by means of controlled exposure, using specific continuous or pulsed sources such as airguns, sonar, or recordings of shipping and pile driving. TTS studies are conducted to determine at which frequencies and received levels TTS is observed (Finneran, 2015). From chinchilla and some other animal through research studies, the relationship between TTS and PTS is known, and, hence, what additional SELs are required above the onset of TTS to obtain PTS (Southall et al., 2007). Methods used for TTS studies are summarized in Finneran et al. (2015). Different studies can use a different definition for TTS. Southall et al. (2007) defines the TTS onset as the exposure needed to produce 6 dB of TTS, but this criterion varies between studies. TTS studies using airguns as a source of sound exposure have been conducted on bottlenose dolphins (*Tursiops truncatus*; Finneran et al., 2015); harbor porpoises (*Phocoena phocoena*; Lucke et al., 2009; Kastelein et al., 2017); and spotted, ringed, and bearded seals (*Phoca largha*, *Pusa hispida*, and *Erignathus barbatus*, respectively; Reichmuth et al., 2016). TTS was not observed in all these studies, and there are different reasons for this. For example, seismic pulses primarily contain low frequencies that may have less of an effect on mid- or high-frequency species groups (Southall et al., 2007, 2019; NMFS, 2016, 2018). Furthermore, in some studies there are indications of self-mitigation by animals. The animals used in these studies can achieve this by actively moving their head away from the sound, by contracting the stapedial muscle in the middle ear (stapedial reflex), or through controlling brain neuronal processes in ways that are not well understood at present (Yost, 1994; Finneran et al., 2015; Nachtigall et al., 2016, 2018; Kastelein et al., 2017).

Also, not all species are equally sensitive, and reaching sufficient high exposure levels in a controlled environment (shallow holding tanks) in a manner that is safe for the animals can be challenging (Finneran et al., 2015; Kastelein et al., 2017). Typically, smaller individual airguns, scaled to the tank volume, are used. The results of TTS exposure studies are summarized in Table 1. TTS in a harbor porpoise was identified by Lucke et al. (2009), using single airgun exposures, with a TTS onset identified at 4 kHz, but not at 32 and 100 kHz, at unweighted SEL of 162 dB re 1 μPa^2s, at weighted SEL of 144 dB re 1 μPa^2s (using NMFS, 2016, criteria), and at peak SPL of 196 dB re 1 µPa. Kastelein et al. (2017) conducted a similar study on harbor porpoises with multiple exposures using two simultaneous firing airguns and found significant TTS levels at 4 kHz at unweighted cSEL of 188 and 191 dB re 1 μPa^2s for 10 and 20 shots, respectively, equivalent to weighted cSEL levels of 140 dB re 1 μPa^2s for 10 shots and 143 dB re 1 μPa^2s for 20 shots (using NMFS, 2016, criteria).

Table 1. Summary of TTS exposure studies using airguns as source

Study	Species	Method	Exposure	TTS onset	TTS frequency
Lucke et al., 2009	Harbor porpoise (*Phocoena phocoena*)	AEP	Single pulse, one airgun, 20 in³, 2,000 psi, 14 to 150 m	Unweighted SEL of 162 dB re 1 µPa²s, weighted SEL of 144 dB re 1 µPa²s (NMFS, 2016), peak SPL of 196 dB re 1 µPa	4 kHz, not at 32 nor 100 kHz
Kastelein et al., 2017	Harbor porpoise	Behaviour	Multiple pulses, 1 to 2 airguns, 5 to 10 in³, 22 to 120 psi, 1 to 2 m	10 to 20 shots of cSEL188 and 191 dB re 1 µPa²s, weighted cSEL of 140.3 dB 1 µPa²s (NMFS, 2016)	4 kHz, not at 0.5, 1, 2, nor 8 kHz
Finneran, 2015	Bottlenose dolphin (*Tursiops truncatus*)	AEP	Single airgun, 10 pulses, 40 to 150 in³, 1,000 to 2,000 psi, 3.9 to 7.9 m	No TTS onset. Max. unweighted cSEL of 193 to 195 dB re 1 µPa²s, weighted cSEL of 174 dB re 1 µPa²s (Southall et al., 2007), maximum SPL_{pk-pk} of 200 to 212 dB re 1 µPa	Not applicable
Reichmuth et al., 2016	Spotted seal (*Phoca largha*)	Behaviour	Single airgun, single pulse, 10 in³, 30 to 100 psi, 1 to 1.5 m	No TTS onset. Unweighted SPL of 165 to 181 dB re 1 µPa²-s, SPL_{pk-pk} of 190 to 207 dB re 1 µPa, weighted cSEL of 171 dB re 1 µPa²-s (Southall et al., 2007) and 156 dB re 1 µPa²s (NMFS, 2016)	Not applicable
Reichmuth et al., 2016	Ringed seal (*Pusa hispida*)	Behaviour	Single airgun, single pulse, 10 in³, 30 to 100 psi, 1 to 1.5 m	No TTS onset. Unweighted SPL of 165 to 181 dB re 1 µPa²s, SPL_{pk-pk} of 190 to 207 dB re 1 µPa, weighted cSEL of 171 dB re 1 µPa²s (Southall et al., 2007) and 156 dB re 1 µPa²-s (NMFS, 2016)	Not applicable

No TTS was observed at 0.5, 1, 2, nor 8 kHz (Kastelein et al., 2017). Finneran (2015) exposed three bottlenose dolphins to 10 seismic pulses at a rate of 10 s between pulses. The maximum unweighted cSEL was 193 to 195 dB re 1 µPa²s, and the weighted cSEL was 174 dB re 1 µPa²s (using Southall et al., 2007, weighted curves for mid-frequency species), with maximum peak-peak SPL of 200 to 212 dB re 1 µPa. Although a small decrease in auditory sensitivity was measured, these exposures did not result in moderate TTS (Finneran, 2015), which was defined in this study as ≥ 10 dB. Reichmuth et al. (2016) exposed trained spotted and ringed seals to single seismic pulses and measured underwater hearing thresholds at 100 Hz. Received unweighted SELs ranged from 165 to 181 dB re 1 µPa²-s and peak-to-peak sound pressures from 190 to 207 dB re 1 µPa but did not result in observed TTS. Maximum weighted cSEL levels were 171 and 156 dB re 1 µPa²s, respectively, when applying the Southall et al. (2007) and NMFS (2016) criteria.

The onset of TTS in healthy marine mammal individuals depends on various physical and biological factors. Relevant physical factors are the received sound pressure and exposure levels by the individuals, the frequency content of the sound, and the interval between pulses in case of pulsed sound as recovery of the hearing system occurs during periods of silence (Kastelein et al., 2019b). Biological factors include species and age of the animals. Due to the limited number of exposure studies, it is often not possible to base PTS criteria on a single sound source type such as airguns. Instead, results from all sources, such as studies using sonar, pile driving, airguns, and others, are grouped together (Southall et al., 2007, 2019; Tougaard et al., 2015). According to Gordon et al. (2004), there is no direct evidence of damage to the hearing systems of marine mammals caused by seismic surveys. Since then, no new observations seem to contradict this conclusion. Studies on bottlenose dolphins, beluga whales (*Delphinapterus leucas*), harbor porpoises, and false killer whales (*Pseudorca crassidens*) suggest that odontocetes have the ability to self-mitigate impacts of loud sounds on their hearing systems by reducing their hearing sensitivity (Supin et al., 2005, 2010; Nachtigall & Supin, 2008, 2014; Linnenschmidt et al., 2012; Supin & Nachtigall, 2013; Finneran et al., 2015, Nachtigall et al., 2016). To what extent this applies to other marine mammal species is currently unknown.

Behavioral Responses, Disturbance, and Stress

Sound-generating E&P activities such as seismic surveys, drilling, or pile driving can result in different types of responses by marine mammals, most of which are considered as disturbance. Responses to anthropogenic marine sound can be grouped into behavioral and physiological responses. Examples of behavioral responses are changes in surfacing, diving, and travel direction, and they include acoustic responses such as changes in vocalization rates (increase, decrease, or cessation). Physiological responses include changes in respiration variables, TTSs, and stress (Nowacek et al., 2007). Southall et al. (2007) categorized behavioral responses into 10 qualitative categories of severity based on observed magnitude of response, ranging from low severity responses (1) such as brief orientation changes to medium severity responses (4-5) such as moderate or extensive changes in locomotion speed, direction, respiration rates, and dive behavior. High severity responses (9) were defined as outright panic, flight, stampede, or stranding events. A summary of many of the response studies from the scientific literature along with the received sound characteristics (frequency and amplitude) is provided in Nowacek et al. (2007).

Behavioral responses by marine mammals to anthropogenic sound sources are observed over a wide range of distances between the source and the animal, with low-severity responses at maximum distances of up to 70 to 80 km (Finley et al., 1990; Erbe & Farmer, 2000). Typically, responses are reversible—that is, upon cessation of the disturbance, the behavior returns to normal (Gailey et al., 2016; Brandt et al., 2018).

Understanding of behavioral responses to airguns and other sound sources originates from field and laboratory studies. In laboratory studies, animals are exposed to predetermined sound levels under controlled conditions by using small airguns or playback of noise recordings as a source (Kastelein et al., 2013; Finneran et al., 2015; Reichmuth et al., 2016). Whereas the SELs in studies with captive animals can be controlled, some disadvantages of these studies include proximity of the receiver to the airgun, limited movement space, inability of the exposed animal(s) to move away from the source, and possible habituation of the animal to the exposure sound. During behavioral response studies (BRSs) in the field, animal behavior in open water is concurrently studied while individuals are exposed to airgun pulses (Dunlop et al., 2016, 2017a, 2017b; Gailey et al., 2016; Table 2). Based on the SLs, sound propagation conditions, and distance to the receiver, the received levels are estimated, and can consequently be used to develop dose-response curves (Gailey et al., 2016; Dunlop et al., 2017b). Some challenges with BRSs in the field are the inability to control the received exposure level by the receiver, to permit restrictions on exposure of animals to loud sound levels out of concern for hearing injury, and to obtain a sufficient sample size to make statistically meaningful conclusions (Dunlop et al., 2012; Gailey et al., 2016). To address the fact that marine mammals cannot be observed while diving, archival or telemetered tags can be attached to marine mammals to record small-scale behavioral responses to anthropogenic activities. Tag sensors can measure depth (pressure sensor), 3-D movement (accelerometer and magnetometer), light (photo sensor), position, and sound exposure (hydrophones) (Miller et al., 2012, 2014; Southall et al., 2012; Sivle et al., 2015; van Beest et al., 2018).

Development of behavioral threshold criteria, like the acoustic metrics used for the onset of injury thresholds (peak SPL and cSEL), to minimize behavioral responses to anthropogenic activities has proven to be difficult. This is mainly because there is typically no straightforward correlation between the severity of response(s) and received exposure levels (Southall et al., 2007; Ellison et al., 2011). Recent studies suggest that in addition to acoustic metrics, the severity of behavioral responses also depend on various factors beyond exposure levels such as (1) the activity state of animals exposed to the sound (e.g., feeding, nursing a calf, migrating, etc.), (2) the type and novelty of a sound, (3) the spatial relations between a sound and the animal hearing the sound (e.g., is the sound approaching or moving away), and (4) age–sex classes (Ellison et al., 2011). Therefore a single number dB threshold as an absolute indication of behavioral disturbance is not reliable, and dose-response curves contain significant variation (Nowacek et al., 2007; Southall et al., 2007; Dunlop et al., 2017b). Learnings from BRSs are presented below.

Malme et al. (1986, 1988) conducted BRSs that examined responses of migrating and feeding gray whales (*Eschrichtius robustus*) to seismic survey sounds in the northern Bering Sea. It was determined that 50% of the whales stopped feeding at received sound pulse levels of 173 dB re 1 μPa (rms). Approximately 10% of the animals interrupted feeding at received pulse levels of 163 dB re 1 μPa (rms). From these studies, 163 dB re 1 μPa has been applied as a behavioral response mitigation threshold during seismic surveys in the direct vicinity of a feeding ground of gray whales off Sakhalin (Yazvenko et al., 2007; Bröker et al., 2015). Despite the application of this mitigation criterion, behavioral responses and changes in distribution, including changes in swim speed,

Table 2. Summary of changes in behavior, vocalization, and stress hormones in airgun studies (unless mentioned otherwise)

Study	Species	Exposure	Observed behavioural change
Behavioural changes			
Malme et al., 1986, 1988	Gray whales (*Eschrichtius robustus*)	163 dB re 1 μPa (rms); 173 dB re 1 μPa (rms)	10% of the whales interrupted feeding; 50% of the whales stopped feeding
Goold, 1996	Common dolphins (*Delphinus delphis*)	133 dB re 1 μPa	Tolerance to these sounds outside a 1 km radius of the airguns
Harris et al., 2001	Ringed (*Phoca hispida*), spotted (*Phoca largha*), and bearded seals (*Erignathus barbatus*)	Presence of seismic survey; no exposure levels provided	Avoidance of the zone closest to the seismic vessel (< 150 m), but no avoidance beyond 250 m from the vessel nor were seals observed to vacate the area of operations.
Madsen et al., 2002	Sperm whales (*Physeter macrocephalus*)	146 dB re 1 μPa (pk-pk); SEL of 124 dB re 1 $\mu Pa^2 s$ (> 20 km)	No observable avoidance or changes in vocalization behaviour were observed.
Yazvenko et al., 2007	Gray whales	< 163 dB re 1 μPa (rms)	Changes in behaviour and distribution (swim speed, reorientation rate, distance from shore, blow interval, and dive time)
Miller et al., 2009	Sperm whales	Seismic surveys @ 1 to 13 km	No response to start-up or approach of an airgun array with a change in behavioural state or direction of movement. Possible change in foraging behaviour.
Robertson et al., 2013, 2015	Bowhead whales (*Balaena mysticetus*)	Presence of seismic survey; no exposure levels provided	Changes in surfacing, respiration, and diving behaviour
Bröker et al., 2015	Gray whales	< 163 dB re 1 μPa (rms)	No significant changes in behaviour or distribution
Dunlop et al., 2016	Humpback whales (*Megaptera novaeangliae*)	105 to 156 dB re 1 $\mu Pa^2 s$	Decreasing dive time and migration movement speed; also identified during controls using the survey vessel without an active source.
Dunlop et al., 2017a	Humpback whales	> 135 dB re 1 $\mu Pa^2 s$ @ 4 km	No abnormal behaviour, but changes in the magnitude and rates of movement patterns, dive/respiratory parameters, and breaching rates; similar changes were detected in the control group as well. Slower migration speeds.
van Beest et al., 2017	Harbor porpoise (*Phocoena phocoena*)	135 to 147 dB re 1 μPa^2-s @ 420 to 690 m	Avoidance behaviour; shorter and shallower dives
Acoustical changes			
Richardson et al., 1990 (drilling recording)	Bowhead whales	115 dB re 1 μPa of playback	Vocalisation response by half of animals in the area
Blackwell et al., 2013	Bowhead whales	80 to 85 cSEL10-min dB re 1 μPa^2-s ~160 cSEL10-min dB re 1 μPa^2-s	Increase in calling rates; animals stopped calling.
Physiological changes			
Thomas et al., 1990 (drilling recording)	Beluga (*Delphinapterus leucas*)	153 dB re 1 μPa @ 1m	No changes in stress hormones (catecholamines)

reorientation rate, distance from shore, blow interval (i.e., respiration rate), and dive time were observed in gray whales during a 3-D seismic survey off Sakhalin in 2001 (Gailey et al., 2007; Johnson et al., 2007; Yazvenko et al., 2007). No changes in behavior were identified during another 3-D seismic survey, however, where the 163 dB re 1 μPa mitigation criterion was used again during a seismic survey in the same location off Sakhalin in 2010 (Bröker et al., 2015; Gailey et al., 2016).

The behavioral responses that were observed during this 2010 seismic survey were associated with vessel proximity, which suggested some non-sound-related disturbance (Bröker et al., 2015; Gailey et al., 2016). As part of this seismic survey, it was hypothesized that gray whale individuals would move closer to shore during the survey, but no significant effects of cumulative sound on distance from shore were observed (Muir et al., 2015). Cumulative sound from the seismic activity over a 3-d period on occupancy and densities suggested avoidance of higher cSELs associated with a prolonged period of exposure, although the influence of prey availability could have caused these changes as well (Muir et al., 2016). BRSs of bowhead whales (*Balaena mysticetus*) to seismic surveys have been conducted since the early 1980s (Richardson et al., 1985, 1986; Ljungblad et al., 1988). Robertson et al. (2013) concluded that changes in behavior, such as displacement, change in blow interval, and surface time exhibited by bowhead whales exposed to seismic operations, are context-dependent. This is supported by other studies, demonstrating that feeding or socializing bowhead whales are less likely to avoid seismic surveys than migrating whales (Richardson et al., 1999; Miller et al., 2005; Koski et al., 2009).

Goold (1996) studied the avoidance behavior of common dolphins (*Delphinus delphis*) to seismic surveys in the Irish Sea. Findings suggested an avoidance reaction by common dolphins to airgun emissions. Observations also suggested tolerance to these sounds outside a 1 km radius of the guns, equivalent to a SPL of 133 dB re 1 μPa. Localized avoidance by ringed, spotted, and bearded seals of a full active seismic array (1,320 in^3) in the Alaskan Beaufort Sea was also observed by Harris et al. (2001), where seals were found to avoid the zone closest to the seismic vessel (< 150 m). No avoidance was observed beyond 250 m from the vessel nor were seals observed to vacate the area of operations. Madsen et al. (2002) investigated the behavior of sperm whales (*Physeter macrocephalus*) in reaction to a distant (> 20 km) seismic survey. Estimated maximum SPLs received at the whales were 146 dB re 1 μPa (pk-pk) and a maximum SEL of 124 dB re 1 μPa^{2}s. No observable avoidance or changes in vocalization behavior were noted during the 13 d of exposure. Dunlop et al. (2016) applied a 20 in^3 single airgun firing at 11-s intervals to expose southward migrating humpback whales (*Megaptera novaeangliae*) on the east coast of Australia. Received SELs ranged from 105 to 156 dB re 1 μPa^2. Animals responded by decreasing dive time and migration movement speed, but this was also identified during controls using the survey vessel without an active source. It was, therefore, suggested that these behavioral changes were a response to the presence of the source vessel. Dunlop et al. (2017a) continued similar exposure studies with a 3,130 in^3 commercial seismic array. Although no abnormal behavior was observed, changes in the magnitude and rates of typical behaviors, such as movement patterns, dive/respiratory parameters, and breaching rates, were detected in response to the full seismic array. These changes were detected in the control group as well (i.e., presence of vessel without active source), leading Dunlop et al. to conclude these were likely responses to the presence of the ship and the airgun sounds. Additionally, slower migratory speeds were observed during airgun exposures, typically within 4 km of the array at received SEL levels over 135 dB re 1 μPa^{2}s. No evidence of significant additional stress was identified during the experimental trials, and behavior of the whales was primarily driven by other whales and the need to socialize and migrate (Dunlop et al., 2017a).

Miller et al. (2009) used acoustic and movement-detecting tags to investigate response of sperm whales to seismic surveys at distances of 1 to 13 km. They concluded that sperm whales did not respond to the start-up or approach of an airgun array with a change in behavioral state or direction of movement. Although not conclusive, the results suggested there was an indication of changes in foraging behavior. Changes in sperm whale foraging behavior in response to low-frequency active sonar (1 to 2 kHz) was observed by Isojunno et al. (2016), where animals switched to a non-foraging state at exposure levels of 131 to 165 dB re 1 μPa. These changes were not observed during exposure to medium-frequency active sonar (6 to 7 kHz) at exposure levels of 73 to 158 dB re 1 μPa.

van Beest et al. (2018) equipped five harbor porpoises with high-resolution location and dive loggers after which they exposed the animals to a 10 in^3 airgun at ranges of 420 to 690 m, with received noise level estimates of 135 to 147 dB re 1 μPa^2-s. One animal displayed rapid and directed movements away from the source, two animals were observed to make shorter and shallower dives than usual, and two animals did not display changes in behaviour.

Stone & Tasker (2006) reviewed marine mammal observer data from 201 seismic surveys conducted in UK waters. They concluded that responses to seismic surveys were taxonomic group-specific; small odontocetes demonstrated the strongest lateral spatial avoidance (i.e., up to beyond line of sight), with mysticetes and killer whales (*Orcinus orca*) displaying more localized spatial avoidance. Long-finned pilot whales (*Globicephala melas*) only adjusted their orientation, and sperm whales showed no statistically significant effects. They also concluded that animal responses to active airguns were greater when large-volume airgun arrays were used in seismic surveys compared to when smaller volumes of airguns were used.

Similarly, Barkaszi et al. (2012) reviewed mitigation observation data collected in the Gulf of Mexico, USA, for the period 2002 to 2008. A total of 194,273 visual survey hours were analyzed, including 3,963 complete sighting records of 28,000 individual animals. There were 32 delays in ramp-ups due to the presence of protected species in the exclusion zone during the 30 min prior to ramp-up, which resulted in a total delay of 18.5 h of down time. Furthermore, for 144 cases, whales, mostly sperm whales, were visually detected in the exclusion zone, resulting in a shutdown of airguns. Shutdowns took on average 58 min, with a total of 125.74 h of down time attributed to shutdowns. The average shutdown frequency for sperm whales was one shutdown for every 1,500 h (or roughly 125 d) of daylight survey operations. The average distance of dolphins to airguns increased with increasing power output. At full power, the mean closest approach of dolphins to airgun arrays was 90% further away than during silent status.

Blackwell et al. (2013) assessed the effects of airgun sounds on bowhead whale calling behavior during the autumn migration in the Alaskan Beaufort Sea. With the start of seismic surveys, call rates increased as soon as airgun pulses were detectable (80 to 85 cSEL10-min dB re 1 μPa^2-s), compared to calling rates without seismic activity. After this initial increase, calling rates leveled off at a received cSEL10-min of ~94 dB re 1 μPa^2-s, and calling rates remained high until cSEL10-min exceeded ~127 dB re 1 μPa^2-s, where whale calling rates began decreasing. Above ~160 cSEL10-min dB re 1 μPa^2-s, whales were virtually silent.

An increase in vocalization rates in response to exposure to a low–medium power technology (sparker) was observed in blue whales (*Balaenoptera musculus*; Di Iorio & Clark, 2010). The authors speculated that this could have been a compensatory behavior to the elevated ambient noise from seismic survey operations (Di Iorio & Clark, 2010). On the contrary, Cerchio et al. (2014) found in a study on the effects of seismic surveys on humpback whale calling rates that there was a significant reduction in the number of whales singing with increasing received level of seismic survey pulses.

Whereas most of the behavioral studies on E&P sources involve use of an airgun array as a source, Richardson et al. (1990) also conducted playback studies of drilling and dredging noise on bowhead whales. Roughly half responded when the received level of noise was about 115 dB re 1 µPa on a broadband basis, or about 110 dB in one 1/3-octave band (20 to 30 dB above ambient). These levels were equivalent to about 3 to 11 km from a drillship and dredge barge in the Canadian Beaufort Sea. As bowheads were seen within 5 km from drilling and dredging activities, Richardson et al. suggested that disturbed animals may habituate to prolonged noise exposure or, alternatively, only the less sensitive individuals may occur at closer proximity to drill ships and dredges.

Exposure to noise is known to cause stress and have the potential to cause changes in hormone levels (Gordon et al., 2004). Few studies have been conducted on the impacts of E&P sound sources on stress levels. Thomas et al. (1990) tried to quantify stress levels by measuring hormone levels (catecholamines) in captive beluga whales exposed to playback of drilling noise (SL 153 dB re 1 µPa @ 1 m) but did not find changes. This could have been attributed to the short exposure periods or adaptions to noisy environments (Gordon et al., 2004).

In summary, behavioral responses depend on a combination of factors such as received levels, habituation, auditory sensitivity, and context (i.e., behavioral state and directionality, and distance to source). Most, if not all, observed behavioral changes in field studies in response to exposure to seismic survey and drilling activities are up to moderate severity (response score 4 to 5 for severity scoring in Southall et al., 2007).

Despite the numerous studies of direct responses of animals to sources of disturbances, it is usually difficult to quantify what effect these responses have on the fitness of the individual and population. Various frameworks have been developed to enhance our understanding of the consequences of behavioral responses of individuals at a population level—often referred to as Population Consequences of Acoustic Disturbance (PCAD) or Population Consequences of Disturbance (PCoD) (Villegas-Amtmann, 2015, 2017; Costa et al., 2016; National Academies of Sciences, Engineering, and Medicine [NAS], 2017; McHuron et al., 2018; Pirotta et al., 2018). In these frameworks, the impact of observed behavioral responses on the health of an individual is first assessed and, consequently, how changes in health affect critical life-history traits such as survival or reproduction. This is usually conducted through development of bio-energetics models that quantify the reduction in bio-energy intake as a function of disturbance and assess this reduction against the bio-energetic need for critical life-history traits such as reproduction and survival (Costa et al., 2016). Finally, the consequences of changes in life-history traits on the development of a population are assessed through population modeling. Although these frameworks are usually complex and under continual development, they have been used to assess the population consequences of disturbance in real-life conditions (Villegas-Amtmann et al., 2015, 2017; Costa et al., 2016; NAS, 2017; McHuron et al., 2018; Pirotta et al., 2018). The PCAD/PCoD model uses and synthesizes data from (behavioral) monitoring programs, ecological studies on animal movement, bio-energetics, prey availability, and mitigation effectiveness to assess the population-level effects of multiple disturbances over time (Costa et al., 2016).

Masking

Auditory masking is the interference of anthropogenic or natural noise with the way in which marine mammals receive acoustic signals for communication, social interaction, foraging, or navigation (Clark et al., 2009; Erbe et al., 2016). Masking can occur when an extraneous sound covers or "masks" a desired sound signal, making the latter more difficult to detect (Nowacek et al., 2007); and masking is quantified as the number of dBs by which an auditory detection threshold is raised in the presence of an interfering sound/noise (ANSI, 2013; Erbe et al., 2016). Masking of sounds needed for key life functions may have a long-term impact on the individual fitness of marine mammals. Our understanding of masking-related impacts on individuals, however, is currently still poorly understood.

Masking depends on a variety of factors that are summarized in a comprehensive overview by Erbe et al. (2016). Relevant variables influencing masking are the location of the vocalizing animal (sender), the sound level, spectral characteristics, and directionality. The signal propagates through the marine environment with variation in acoustic properties. At the location of the receiver, the natural and/or anthropogenic noise levels determine the level of potential masking. Additionally, characteristics of an animal's hearing system, such as sensitivity and different types of masking release, are examples of important variables at the receiver end (Erbe et al., 2016). Masking release refers to the process and the amount by which expected masking is decreased by some manipulation of the masking or target sound (Oxenham, 2014). Examples of anti-masking strategies are frequency and amplitude comodulating—that is, varying the pitch and loudness by altering the vocalization characteristics in the presence of noise (Scheifele et al., 2005; Holt et al., 2011; Hotchkin & Parks, 2013; Dunlop et al., 2014; Erbe et al., 2016). Reichmuth (2012) states that current models of auditory masking in marine mammals oversimplify hearing in realistic environments and recommends systematic and progressive studies using psychoacoustic methods (i.e., studies on sound perception) to gain a better understanding of masking effects. Sills & Reichmuth (2016) conducted a masking study using airgun pulses recorded at 1 and 30 km away from an active array. Spotted and ringed seals were trained to detect a low-frequency tone (100 Hz) within these pulses to evaluate how airgun sounds can interfere with detection of low-frequency sound. A second objective was to determine how standard audiometric data (such as audiograms) can predict the extent of masking. Sills and colleagues concluded that critical ratios alone are not sufficient to predict the full range of observed temporal and spectral variation in masking present, and they proposed how masking models can be improved by incorporating time-based analysis of signals and the masking noise (Sills & Reichmuth, 2016; Sills et al., 2017). A critical ratio is the difference between the SPL of a pure tone just audible in the presence of a continuous noise of constant spectral density and the sound pressure spectrum level for that noise expressed in dBs (ANSI, 2013).

Monitoring

To reliably assess and mitigate the impacts of hydrocarbon E&P activities on marine mammal individuals or populations, numerous source-pathway-receiver (SPR) parameters must be understood. When information gaps are identified, such as the seasonality of a marine mammal population presence, the accuracy of acoustic propagation modeling results, or the effectiveness of certain mitigation measures, monitoring studies can be implemented to fill these key knowledge gaps. The most common types of monitoring programs implemented as part of E&P operations are categorized according to the SPR model (Table 3).

Source

Sound Source Characterization Studies—Measurements of the acoustic characteristics of E&P sources are usually conducted at different distances from the source. As airgun arrays and drilling vessels are not point sources, the multiple sound sources (e.g., individual airguns) create a near-field acoustic environment in which the sound field consists of complex interactions among the sound waves created by the individual sources. As the sound waves are not in phase, the complex interactions consist of constructive and destructive interference (Jiménez-Arranz et al., 2017). At some distance away from the source, a far-field environment is developed in which the wave fronts from the individual sources add in phase and produce plane wave fronts (Richardson

Table 3. Overview of the types of monitoring conducted to understand relevant aspects of the source, pathway, and receiver of marine sound and impacts on marine mammals

Source	Sound source characterization Sound source verification
Pathway	Acoustic monitoring studies Propagation modeling verification Propagation model parameterization
Receiver	Abundance, density, and distribution Systematic surveys (distance sampling) (aerial- and vessel-based) Shore-based distribution surveys Mark-recapture Photo-identification Passive acoustic monitoring Marine mammal observers Monitoring of mitigation efficacy Behavior Behavioral response studies Theodolite tracking Focal follow

et al., 1995). Acoustic monitoring is typically conducted in the far-field. As SLs are mostly provided at 1 m away from the source, far-field measurements are back-propagated to calculate the theoretical SLs at 1 m from the source. Environmental and physical parameters are required to accurately model SLs, which brings a degree of uncertainty when estimating SLs. Multiple measurements at different distances, therefore, result in a more accurate estimate of the SL. For non-point sources such as airgun arrays and drilling vessels, back-propagated SLs are higher than actual measured levels because of the destructive interference of each airgun, and not all pressure peaks arrive at the receiver at the same time (Caldwell & Dragoset, 2000). So, whereas the effective SL predicts pressures in the far-field of the array that can be up to 260 dB peak re 1 µPa, in the near-field, the maximum pressure levels encountered are generally limited to between 220 and 230 dB peak re 1 µPa (Hildebrand, 2009). Numerous sound source characterization studies of seismic sources and drilling activities have been conducted to determine SLs, many of which were conducted in the Alaskan Beaufort and Chukchi Seas. Few peer-reviewed publications are available, and most of these data are available in reports and grey literature (Jiménez-Arranz et al., 2017).

Sound Source Verification (SSV) Studies—SSV studies are conducted to determine the accuracy of modeling results. Some seismic good practice guidelines propose the use of an exclusion zone based on a fixed distance from the airgun array. For example, the Joint Nature Conservation Committee (JNCC) (2017) recommends a fixed exclusion zone of 500 m, which should be monitored prior and during ramp-up. If animals are observed within this exclusion zone, start of the survey must be delayed. In other jurisdictions, the airguns must also be shut down when a marine mammal is observed in the exclusion zone or when approaching this zone *during* active airgun operation. Other guidelines propose the use of exclusion zones based on acoustic thresholds (Southall et al., 2007; Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea, and Contiguous Atlantic Area [ACCOBAMS], 2013; NMFS, 2000, 2016, 2018). When acoustic thresholds are used, the exclusion zone radius around a source depends on the source configurations; depth of the source in the water; and environmental parameters such as sound speed profile, water depth, bathymetry, and subsurface sediment or rock density. General assumptions about these variables are made during development of the propagation model. SSV measurements are conducted to quantify the accuracy of the propagation model results and the estimated exclusion zone. SSV measurements are made by linearly deploying several acoustic recorders (2 to 5) at various distances from a source. In the case of SSV to determine exclusion zones, the vessel will approach the array perpendicularly. Measurements at the broadside of a source are then used to determine the exact distance from the source to the relevant acoustic threshold by developing regression curves between measured sound levels at the different distances from the source (Figure 2). Racca et al. (2015) provided a detailed outline of an SSV experiment and how modeled exclusion zones are modified based on the outcome of SSV measurements. Aerts & Streever (2016) compared modeled and measured underwater sound isopleths conducted as part of seismic surveys in the Chukchi Sea, Alaska. They found a poor agreement between modeled and measured results that was thought to result from natural variability in the marine environment, the application of precautionary correction factors, and data interpretation in the generation of the modeled sound isopleths.

Pathway

Propagation Modeling Verification Studies—SSV studies are mostly conducted to determine the radius of an exclusion zone around a sound source that is generally less than 1 km, but they can also be used to verify the accuracy of modeling results over larger distances (Martin et al., 2017). The latter is not common, but it is occasionally done when there are areas of specific concern further away from the survey such as breeding or feeding grounds of endangered populations of marine

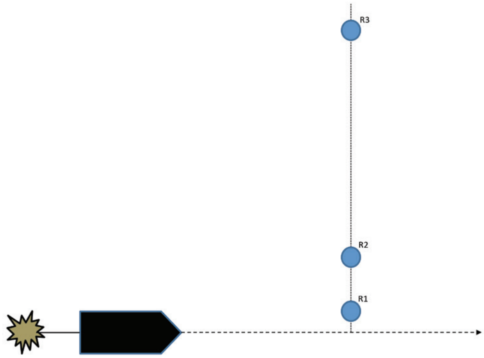

Figure 2. Schematic overview of a typical sound source verification (SSV) experiment. In this example, three recorders are used (R1, R2, and R3), though this number can vary. The farthest recorder is often placed at the expected location where an acoustic threshold (injury or behavior) is expected to occur to verify that modeled results are accurate.

mammals (Racca et al., 2015; Martin et al., 2017). Because of the concern of potential impacts from a seismic survey in Baffin Bay on a summer resident population of narwhal in Melville Bay, Martin et al. (2017) modeled sound levels up to 100 km away from the airgun source. Acoustic recorders were deployed at various distances to verify the modeling results. It was found that pre-survey estimates of the received sound levels were 3 to 7 dB higher than the levels measured at distances from 0.5 to 65 km away. Model parameters, such as sound speed profile and bathymetry, were adjusted and resulted in better alignment with differences of 0 to 4 dB. In special circumstances, SSV studies can also be done in real time. Racca et al. (2015) reports on a unique real-time SSV program to ensure that the exposure levels of gray whales off Sakhalin, Russia, did not exceed the acoustic thresholds set for behavioral responses.

Model Parameterization Studies—Propagation modeling studies require accurate environmental data on depth, sound speed profiles, bathymetry, and subsurface density (Urick, 1983). Seasonal changes in these parameters, such as water temperature, will influence the outcome of propagation models (Racca et al., 2015). Oceanographic data can be collected in advance, at the start of E&P activities, or may be available through long-term data collection programs. Sound speed profiles are obtained by deploying a CTD (conductivity, temperature, and depth) sensor that measures conductivity (salinity) and temperature as a function of depth. Salinity, temperature, and pressure are used to determine the density of water, which influences sound propagation.

Receiver

Abundance, Density, and Distribution—Knowledge of the abundance, density, and distribution of marine mammals is needed to assess the vulnerability and conservation status of a population (Muir et al., 2016; Bröker et al., 2019). Insights to the abundance and distribution of marine mammal populations can be difficult to obtain due to the remoteness, migration and distribution patterns, and cryptic behavior of different marine mammal species. Several techniques have been developed such as aerial- and vessel-based line-transect surveys (Buckland et al., 2001), mark-recapture studies (Hammond, 1986; Hammond et al., 1990), and, more recently, passive acoustic monitoring (PAM) (Marques et al., 2009; Küsel et al., 2011). Additionally, data on abundance and distribution are required to determine the impacts of human activities, such as harvesting or resource development, on marine mammal populations. During impact monitoring studies, these parameters (i.e., abundance and distribution) are typically assessed before, sometimes during, and after an activity (e.g., Muir et al., 2015).

Systematic Surveys (Distance Sampling)—Systematic surveys of marine mammal populations are conducted to collect population abundance and distribution data. These surveys are typically conducted by humans on observation platforms, such as line-transect surveys from vessels or airplanes (Buckland et al., 2001; Rekdal, et al., 2015; Bröker et al., 2019), or point surveys from shore-based stations (e.g., Muir et al., 2015, 2016; Gailey et al., 2016), using distant sampling methodologies as outlined in Buckland et al. (2001). More recently, surveys are also conducted using a combination of autonomous technology (unmanned aerial vehicles), still photography, or video (e.g., Koski et al., 2013, 2015; Bröker et al., 2019). During systematic surveys, a pre-planned pattern is surveyed for presence of marine mammals. Correction factors are applied for availability (i.e., average time animals spend at the surface during which animals can be detected) and distance-dependent detection rates (i.e., correction for missed animals farther away from the track-line or observation point). The variance in the observational data is then used to estimate a confidence interval around the abundance estimate (Buckland et al., 2002). The main advantages of aerial surveys over vessel-based surveys are (1) the ability to cover larger areas per unit time, (2) reduced disturbance of animals, (3) less dependence on sea state, and (4) reduced cost as the charge rate for suitable vessels is typically high, especially in Arctic regions (Henkel et al., 2007). Disadvantages of aerial surveys are (1) human safety concerns; (2) higher dependence on weather conditions—for example, low cloud cover can prevent aerial surveys from flying at target observation altitudes while vessel-based surveys are not affected by low cloud cover as long as the horizon is visible; (3) limits on the distance between the survey area and a shore-based landing strip; (4) fuel-limited survey effort when the survey area is far from land (Hodgson et al., 2013); and (5) a narrower swath during aircraft-based surveys than during vessel-based surveys (Koski et al., 2015).

Mark-Recapture—Mark-recapture studies are conducted to determine changes in abundance of a population. The basic concept of a mark-recapture effort is to sample and mark several individuals from a population and then release them back into the population, with subsequent resampling of individuals to determine the proportion of marked individuals. The population estimate ($\hat{N}$) is determined by ($\hat{N}$) = (M*T)/R, with M = number of marked individuals, T = total recaptured individuals, and R = number of marked recaptures. The assumptions underlying these models are provided in Urian et al. (2015). Marking of marine mammals is done using different methods such as photo-identification, genetics, or tags. The most commonly used methodology is non-invasive through photo-identification, where individuals in a population are repeatedly photographed (seasonally and/or annually). Individuals can then be recognized by skin patterns such as pigment spot patterns and scars (Tyurneva et al., 2010), fluke (Katona et al., 1979), or the shape of dorsal fin (Würsig & Würsig, 1977; Würsig & Jefferson, 1990). The first identification equals the "mark" of an individual, with subsequent identifications being the "recaptures." Individuals can also be "marked" through their DNA profile or genetic footprint. This involves taking a tissue sample, often a skin biopsy, from which an individual can be distinguished based on mitochondrial haplotypes and microsatellite markers (Hammond, 1986; Palsbøll et al., 1997; Palsbøll, 1999; Smith et al., 1999; Rekdal et al., 2015). A combination of photo-identification and genetic identification mark-recapture efforts is also possible if skin samples are taken from individuals that have been photo-identified. Lastly, as pinnipeds can be approached on shore, branding or long-lasting tags can be applied on flippers to mark individuals (Pistorius et al., 2000; Wilkinson et al., 2011), although there is a risk of tag loss that will influence the outcome of mark-recapture efforts (Schwarz et al., 2012).

Photo-Identification—Recognition of individuals through photo-identification efforts are also used for numerous other objectives, which are summarized in Hammond et al. (1990). In addition to mark-recapture studies, a main purpose of photo-identification is to determine reproductive rates and calf and adult survival rates, both relevant to monitor population dynamics (Bradford et al., 2006). Additionally, results from photo-identification studies provide insight into individuals' fine- and large-scale migration patterns such as movement between feeding grounds (Tyurneva et al., 2010) and migration between feeding and breeding grounds (Weller et al., 2012). Inter- and/or intra-annual changes in body conditions can be derived from photo-identification studies as well, which can be important to detect potential impacts of disturbance caused by E&P activities (Bradford et al., 2008). Anthropogenic disturbance has the potential to influence the bio-energetic requirements of marine mammal individuals (Villegas-Amtmann et al., 2015, 2017), making body condition a useful parameter to monitor.

Passive Acoustic Measurements (PAM)—PAM is used to monitor for presence/absence as well as proximity of marine mammal species (e.g., Frouin-Mouy et al., 2017; Verfuss et al., 2018) and has been conducted since the early 1990s (Sousa-Lima et al., 2013). Relatively novel methodologies have been developed to determine the size and density of cetacean populations by using acoustic sensors to record vocalizations (Barlow & Taylor, 2005; Marques et al., 2009; Küsel et al., 2011). Most density estimation methods are based on estimates of the probability of detecting vocalizations as functions of distance (Küsel et al., 2011). The number of acoustic cues (vocalizations) are then used to estimate cetacean densities by making assumptions on the probability of detecting cues, cue rates, and the proportion of false positive detections (Marques et al., 2009). Acoustic tags are often applied to individual animals to obtain insights about cue rates.

The advantage of PAM over visual surveys is that marine mammals can only be visually detected in daylight and good weather conditions. Additionally, some species (e.g., beaked whales) are difficult to detect due to their long dive behavior. Especially in remote and inaccessible areas, such as ice-covered areas, PAM can have advantages (Frouin-Mouy et al., 2017). Furthermore, visual surveys can be expensive due to cost associated with vessel or plane hire. A key disadvantage of PAM is lack of detection when a focal species is not vocalizing; sound production is a requirement for PAM to be successful. More information on PAM systems and methods is provided in Mellinger et al. (2007) and Verfuss et al. (2018).

Marine Mammal Observers—During most seismic surveys, marine mammal observers (MMOs), also referred to as protected species observers (PSOs) in the United States, monitor for the presence of marine mammals around the seismic or drilling vessel. Depending on the country of operation, there are differences in the number of required MMOs during E&P activities, their role, and the level of training needed. Typically, they are tasked with conducting a pre-survey scan prior to activating the seismic airgun source, ensuring the exclusion zone is clear of marine mammals and sometimes other species, such as sea turtles, before and during ramp-up. And, in most cases, MMOs monitor for presence of marine mammals in the exclusion zone during seismic acquisition. Upon observing animals in the exclusion zone before ramp-up or during ramp-up or acquisition, the MMO will make the airgun operator aware of the presence of marine mammals so that delay or a shutdown can be made. For this reason, MMOs have an important role in implementation of seismic survey monitoring and mitigation plans. In most surveys, one or two MMOs are on duty during seismic acquisition with shift limitations between 2 to 4 h. In addition to implementing mitigative actions, MMOs collect systematic data on observed marine mammal species, environmental conditions, and project activities. Although MMO data are not typically used to assess population abundance, this information provides useful presence/absence and distribution data of marine mammal species. Additionally, MMO data are analyzed to determine the effects of seismic surveys on marine mammal behavior, how well mitigative measures are applied, and the efficacy of mitigation measures (Stone, 2015a, 2015b). MMOs can effectively monitor a zone of approximately 2 km around a seismic vessel in suitable conditions. Monitoring is limited by poor weather conditions or nighttime when visual observations are not effective; in these cases, PAM is often used instead. Use of PAM during poor visibility conditions can be a regulatory requirement in a number of countries.

Behavioral Response Studies—The advantages and disadvantages of different types of behavioral responses studies and key results from BRSs to airguns were summarized in the "Behavioral Responses, Disturbance, and Stress" section.

Mitigation

E&P companies conduct environmental impact assessments (EIAs) for most significant E&P activities, such as seismic surveys or drilling, in most regulated jurisdictions around the globe. The purpose of an EIA is to describe the activity, outline the regulatory framework and requirements, identify the environmental aspects, assess the single and cumulative environmental impacts, provide a plan to mitigate the identified risk, and assess if the residual risk is acceptable. Impacts are usually mitigated to meet regulatory established impact thresholds or until the residual impacts are reduced to *As Low As Reasonably Practical* (ALARP) (International Association of Oil and Gas Producers [IOGP], 2010; Petersen & Valeur, 2013). ALARP means that the amount of mitigative effort and, thus, the time, cost, and logistics associated with those mitigative measures should be in line with the assessed risks. If the risk to a marine mammal population is low, it is reasonable to apply less stringent mitigation measures, compared to when risks are high, which requires more mitigative action.

Various frameworks for risk assessments of E&P activities are available (Kyhn et al., 2011; Wood et al., 2012; Nowacek et al., 2013; Danish Centre of Environment and Energy [DCE], 2015; NMFS, 2016, 2018; Forney et al., 2017). Additionally, there are numerous guidelines for mitigation of E&P activity impacts, both developed by the E&P industry (IOGP, 2017) or by regulatory and environmental organizations (Prideaux & Prideaux, 2015; JNCC, 2017). In addition to guidelines, agencies regulating E&P activities often prescribe what mitigative measures are needed to avoid and minimize possible impacts from E&P sound sources (Weir & Dolman, 2007; Environment Protection and Biodiversity Conservation Act [EPBC], 2008; Department of Conservation [DOC], 2013; DCE 2015; Fisheries and Oceans Canada [DFO], 2016; NMFS, 2016, 2018).

A range of mitigation measures can be applied to address the impacts of E&P activities on marine mammals. These measures can be categorized based on the mitigation hierarchy, a concept first introduced by the International Finance Corporation (IFC) (2012). The different sequential steps in the mitigation hierarchy to minimize impacts of E&P activities are (1) avoidance, (2) reduction, (3) restoration, and, eventually, (4) offsetting (Figure 3).

Whereas the third and fourth steps (restoration and offsets) in this mitigation hierarchy are being applied in terrestrial environments, the application of these steps in marine environments, specifically with regards to managing noise impacts related to marine mammals, is difficult to achieve (Jacob et al., 2016; Milner-Gulland et al., 2018). This is because both the impacts of E&P activities on marine mammal populations and the effectiveness of restoration and offsetting activities are challenging to quantify. Most mitigation measures currently applied belong in the first two steps of this mitigation hierarchy.

The following section provides an overview of the full suite of measures available for inclusion in marine mammal mitigation plans for E&P activities and brings together the current understanding of impacts and mitigations of marine sound from E&P activities. It is the author's view that mitigation plans should be developed in line with the assessed risk of the activity—that is, effective and efficient mitigation plans are developed in line with the ALARP principle.

Avoidance

The most effective way of managing potential impacts of E&P activities on marine mammal populations is avoidance of overlap between activities and populations in space and time (Nowacek et al., 2013; Bröker et al., 2015). Avoiding impacts can be achieved when marine mammal populations are absent from the vicinity of exploration or production areas for part of the year. This can be the case when populations have migratory patterns between summer feeding grounds and winter breeding grounds as is the case for most mysticetes (Nowacek et al., 2015). Some odontocetes also follow annual migratory patterns—for example, a narwhal population off west Greenland that resides in northern summer areas and overwinters in lower latitude areas (Heide-Jørgensen et al., 2003). When E&P activities can be scheduled for periods when populations are not present or only in low numbers, the potential impacts will be largely avoided. Avoidance of impacts can be conducted on a voluntary basis by E&P companies or can be directed by regulatory agencies. One example is described in Bröker et al. (2015) in which a seismic survey was conducted near the summer feeding grounds of a critically endangered population of gray whales off Sakhalin in 2010. The primary mitigation measure was to complete the survey before the arrival of most individuals and cow–calf pairs. Another example relates to the previously mentioned population of narwhal that reside in the summer in Melville Bay, Greenland, and migrate to a lower latitude towards the end of September and October. Due to concern over disturbance resulting in possible ice-entrapment, the Danish Centre of Environment and Energy (DCE) made it a requirement that seismic survey campaigns be completed by 15 October (Kyhn et al., 2011; Heide-Jørgensen et al., 2013). In certain areas, temporal planning around presence of marine mammal populations can be challenging or impossible due to restrictive ice or weather conditions or the presence of marine mammals, or other sensitive marine species, year round. Avoidance of overlap between E&P activities and presence of marine mammal populations requires data in population dynamics such as feeding and breeding locations and seasonality, and migration patterns and timing.

Minimization

There are various mitigation measures that can be applied to minimize the potential impacts of E&P activities on marine mammals. Measures involve the reduction of activity-related sound levels, minimizing unnecessary high frequencies generated in seismic surveys, and ensuring that marine mammals are not exposed to sound levels potentially resulting in auditory injury.

Reduction of Activity-Related Sound Levels—Sound SLs of airgun arrays increase with larger volume arrays. Sound source pressure levels must be of sufficient strength to illuminate the areas of industrial or scientific interest, typically at depths of 7 km or more (Gisiner, 2016). It is good practice to design arrays that have the lowest sound source pressure levels required to obtain satisfactory

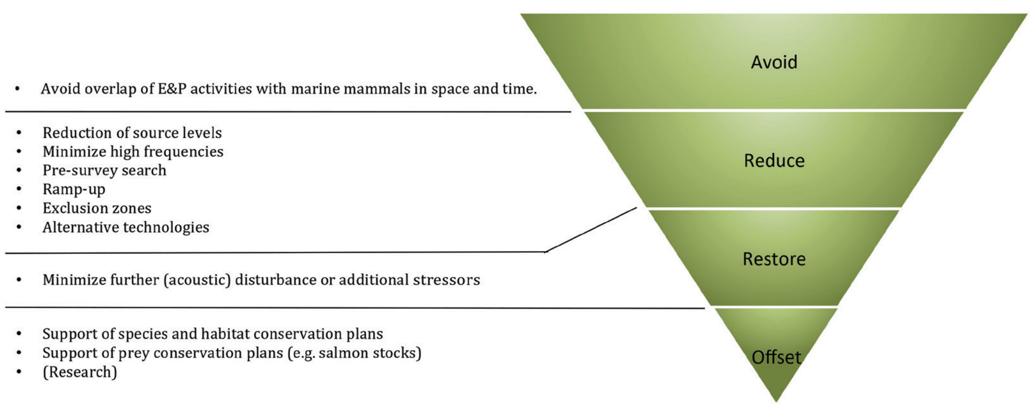

Figure 3. The mitigation hierarchy with different measures to avoid and minimize impacts of E&P sound sources on marine mammals

data, and to not excessively use unnecessarily large arrays. Arrays should also be designed in a way that maximizes downward propagation and minimal horizontal propagation.

Explosives were used as the main energy source during marine seismic surveys until the mid-1960s (Fitch & Young, 1948; Richardson et al., 1995). For several reasons, safety especially, explosives were replaced with water- and airguns as the seismic source (Lugg, 1979; Hutchinson & Detrick, 1983). Watergun pulses contain more high frequencies in comparison to airguns and are a good source for very high-resolution surveys but have relatively limited penetration (Hutchinson & Detrick, 1984; Richardson et al., 1995). These days, airguns are the main source used during hydrocarbon exploration, development, and production. This is because airguns have the optimal combination of lower cost, high SL, low-frequency sound, and relatively low-pressure pulse rise-time (~5 ms) in comparison with chemical explosives (< 1 ms) and waterguns as related to concerns over barotrauma and better safety (Hutchinson & Detrick, 1983; Urick, 1983; Richardson et al., 1995). Marine vibrators are an alternative source that, in certain situations, have the potential to replace airguns. They produce a continuous sound at lower source pressure levels, with the main advantage being the absence of medium and high frequencies (< 250 Hz). Thus, the risk of auditory injury is much lower as compared to airguns. However, at present, it is not well understood how the risk of disturbance and/or masking caused by marine vibrators compares to airguns. Comparative risk assessments are currently underway to obtain greater insight to the environmental advantages of this alternative source (LGL & MAI, 2011). Marine vibrators have been utilized for hydrocarbon exploration but are not yet commonly used (Laws et al., 2018). There are various efforts ongoing in the E&P industry to further advance this technology and make it commercially available (Feltham et al., 2017).

A commercially available technology to reduce sound source pressure levels around stationary sources, such as pile driving or drilling rigs, are bubble/resonator curtains that are placed around a point source. Bubble curtains are commonly used around pile-driving activities and are effective in reducing SLs by ~10 to 20 dB (Würsig et al., 2000; Matuschek & Betke, 2009; Lucke et al., 2011). Bubble curtains can consist of free-flowing bubbles, encapsulated bubbles, or resonator shields. At present, bubble curtains cannot be applied around moving sources, such as airgun arrays, due to size, weight, and drag, or at deeper depth due to higher pressures.

Minimize High Frequencies—Most of the energy in airgun pulses is in the 5 to 200 Hz bandwidth. However, airguns produce frequencies of up to 16 kHz (Landrø et al., 2011; Martin et al., 2017), which overlaps with the best auditory ranges of some odontocetes. These higher frequencies (i.e., above 200 Hz) have no utility for subsurface imaging due to their lower ability to penetrate the substrate. Minimizing high frequencies in airgun pulses is, therefore, an effective way of reducing potential injury and disturbance zones for odontocetes around an airgun array. Recent developments in airgun design have resulted in a commercially available airgun with reduced acoustic output at high frequencies, which was achieved by redesign of the mechanisms that control the release of air (Coste et al., 2014; Gerez et al., 2015; Supawala et al., 2017).

Pre-Survey Marine Mammal Search—Prior to the start of the airgun ramp-up sequence, a pre-survey search is typically conducted by MMOs to ensure no animals are in the direct vicinity of the array (see above). If animals are seen within the pre-defined exclusion zone, ramp-up or start of the array is delayed until the exclusion zone is cleared. Pre-survey searches are usually conducted for a minimum of 20 to 30 min, and up to 60 to 120 min in deep water where deep-diving marine mammal species may be present or in new locations under poor visibility conditions (DOC, 2013).

Ramp-up—Ramp-up, also called soft-start, is the systematic increase of acoustic output of a source over the course of 20 to 40 min (Ainslie & von Benda-Beckmann, 2013). The application of a ramp-up procedure is standard practice in most activities with a risk of causing disturbance or thresholds shifts such as pile driving and seismic surveys. In seismic surveys, this is achieved by starting with the smallest airgun in the array and gradually adding other airguns and/or increasing the pressure. The objective of ramp-ups is to reduce the likelihood of hearing damage or severe behavioral responses. The assumption behind ramp-ups is that exposure of marine mammals to lower sound levels results in movement away from the direct vicinity of airguns, thus preventing exposure to high sound levels when the array is fully operational (Weir & Dolman, 2007). Ramp-ups are usually conducted prior to the start of every acquisition line or when the array has been silent for a certain period (10 to 20 min). Although the application of ramp-ups is included in all available seismic guidelines and regulatory requirements (Weir & Dolman, 2007; Australian Government Department of the Environment, Water, Heritage and the Arts [DEWHA], 2008; ACCOBAMS, 2013; DOC, 2013; DCE, 2015;

DFO, 2016; NMFS, 2016, 2018; JNCC, 2017), the way it is conducted varies widely, and the efficacy of this mitigation measure is not entirely understood. The only systematic study on efficacy of ramp-up of seismic airgun arrays was conducted by Dunlop et al. (2016), who studied responses of migrating Australian humpbacks to ramp-up by using an array of six airguns with the smallest being 20 in^3. Dunlop et al. found that humpback groups increased their distance from the source; however, the initial level of the ramp-up was not found to be relevant, and neither was the source nor received level throughout the exposure phase. The presence of the source vessel without an active source was also found to have an effect on humpback avoidance behavior. Despite these findings, Dunlop et al. concluded that a ramp-up procedure could be effective in keeping groups away from the source as most groups changed movement to increase distance from the source vessel. Stone (2015a) analyzed 190.000 h of MMO and PAM data, with active source activity 39% of the time. Based on 9,073 sightings or acoustic detections of marine mammals, comprising 124,024 individuals, it was concluded that the use of a ramp-up may be an effective measure. This was because fewer individuals were observed near the vessel during ramp-up, and more animals were observed avoiding or traveling away from the seismic vessel. In a study on the effectiveness of ramp-up as part of sonar operations, it was found that ramp-up procedures before full-level sonar operations can reduce the risk of hearing threshold shifts with marine mammals but that their effectiveness depended strongly on the responsiveness of the exposed animals (Ainslie & von Benda-Beckmann, 2013; von Benda-Beckmann et al., 2013, 2016). In the case of humpback whales, ramp-up was not found to be an effective mitigation measure to reduce the risk of physiological effects as most whales did not exhibit a strong avoidance response to sonar signals (Wensveen et al., 2017). This study also indicated that ramp-up of sonar reduces risk more effectively in situations in which animals are more responsive—for example, when animals are in a non-feeding or reproductive state, suggesting that ramp-up is more effective in species that are more behaviorally responsive (Wensveen et al., 2017).

Exclusion Zones—A key mitigation measure to reduce the likelihood of auditory damage due to exposure from high sound levels is the use of exclusion zones, also called injury, mitigation, or safety zones (NMFS, 2016, 2018; JNCC, 2017). Exclusion zones are zones around a sound source that are monitored for presence of marine mammals by MMOs or PAM systems. Exclusion zones in the E&P industry are mainly used during seismic survey operations but occasionally also for other activities such as pile driving or drilling. The width of exclusion zones varies dependent on regulatory requirements, SLs, and species of concern. Exclusion zones around a seismic array can have either a fixed radius—for example, 500 m around the source as recommended by DEWHA (2008) and JNCC (2017)—or modeled distances to regulatory acoustic thresholds. Acoustic thresholds for mitigation zones are based on peak pressure or M-weighted SELs (Southall et al., 2007, 2019; NMFS, 2016, 2018). Some guidelines assume that animals naturally avoid the exclusion zones due to the presence of loud sound sources and do not require shutdown of the source during seismic acquisition (e.g., JNCC, 2017). Other guidelines and regulations require monitoring of exclusion zones during operations as well, including shutdown of the source upon detecting marine mammals within this zone during operations to avoid risks of auditory injury. Whereas exclusion zones are used in most seismic surveys to avoid auditory injury, use of exclusion zones to mitigate behavioral responses is not common in the E&P industry. Reasons for this include (1) the exclusion zones where potential behavioral disturbance occurs are too large to effectively monitor for presence of marine mammals, (2) the number of shutdowns could be so large that the survey would be impossible to complete, and (3) the lack of evidence that seismic surveys cause a decline in population size through disturbance or behavioral responses to individual animals as most responses appear to be of moderate severity (response score 4 to 5 for severity scoring in Southall et al., 2007). Use of behavioral exclusion zones have been applied when seismic surveys are conducted near critically endangered populations, near important feeding or breeding groups, or when multiple other disruptive anthropogenic activities are ongoing. Examples of use of exclusion zones to mitigate for behavioral responses are provided in Johnson et al. (2007) and Bröker et al. (2015), who report on seismic operations near a small population of western gray whales off Sakhalin.

Use of Mitigation Airguns—Line turns during seismic surveys can take several hours (Bröker et al., 2015), during which the airguns are switched off. Some seismic guidelines recommend continued use of the smallest airgun array during these line turns (i.e., when the full array is not active) to continue to deter marine mammals away from the seismic vessel (DOC, 2013; DCE, 2015). The efficacy of this mitigation measure, however, has not been demonstrated and introduces additional acoustic energy into the marine environment. Additionally, this mitigation measure can be impractical for technical reasons as line turns are often used to depressurize and service the airgun arrays and may cause some safety concerns (Bröker et al., 2015).

Restoration

Defining mitigation measures to restore the impacts of acoustic exposure to E&P sound sources are currently not applied, mainly due to difficulties in quantifying impacts and identifying action to negate those impacts after they may have occurred. One (theoretical) measure is to ensure that other potential sources of disturbance in the vicinity, such as other activities generating loud sound levels, are eliminated or minimized. In this way, exposed individuals can continue with their pre-disturbance activities (e.g., feeding) without experiencing additional and compounding impacts, and their hearing systems can recover.

Offsetting

Offsetting of environmental impacts caused by marine sound is a new and unexplored field, which is in need of better guidelines and case studies. At present, there are no clear examples of offsetting efforts to mitigate impacts on marine mammal populations that are applied in the E&P industry. This is mainly due to the absence of significant impacts due to regulatory requirements to minimize potential impacts, and the difficulty in quantifying impacts and identification of appropriate offsetting measures. During various E&P activities, extensive monitoring and scientific programs have been implemented to enhance the understanding of marine mammal ecology and impacts of exploration activities on marine mammal populations. Whether monitoring, research, or information gathering should be considered as an offset is an area of active controversy (Milner-Gulland et al., 2018). Research could reduce uncertainty and promote innovation, which may be a prelude to later mitigation or avoidance activities once more is known about the biological setting (Milner-Gulland et al., 2018). In terrestrial environments, where the concept of offsetting is more mature, research is not considered as an appropriate offset (Bull et al., 2016). An example of offsetting impacts on marine mammal populations by E&P activities could be the initiation or funding of conservation programs focused on either reducing risks to a specific population or species, or on the protection of the habitat that is important to that population or species. Theoretical examples of offset activities could be financial contributions towards funding of entanglement or ship strike reduction programs, or coast guard patrols and/or legal action against illegal and harmful fishing activities that could result in entanglement or bycatch of marine mammals (Rojas-Bracho & Reeves, 2013; Weller et al., 2014).

International Guidelines

Numerous national and regional guidelines and legislative requirements have been developed to mitigate the potential impacts of E&P activities on marine mammal populations. An overview of available guidelines is provided in Weir & Dolman (2007). In absence of national guidelines or requirements, the JNCC (2017) guidelines are one of the most commonly applied guidelines in the E&P industry. The International Organization of Oil and Gas Producers (IOGP) and the International Association of Geophysical Contractors (IAGC) jointly developed a recommended set of monitoring and mitigation measures for cetaceans during marine seismic survey geophysical operations (IOGP, 2017), which are quite similar to the JNCC (2017) guidelines. While the JNCC guidelines have been criticized for lacking a scientific basis because of arbitrary exclusion zone size and lack of shutdown guidance (Wright & Cosentino, 2015), the E&P industry has found some other guidelines overly precautionary due to requirements for extensive monitoring and mitigation independent of the assessed risk to marine mammals. Most seismic surveys are different in terms of risks to marine mammal populations based on differences in area, airgun array size, species presence, animal abundance and distribution, duration, etc.; therefore, it is recommended that mitigation plans should be developed in line with those risks (Nowacek et al., 2013). The E&P industry often refers to the ALARP approach as a way to align risks with proposed mitigations. Whereas for normal, low-risk seismic surveys, the JNCC (2017) guidelines may be sufficient, for high-risk operations, additional, more stringent mitigation measures may be necessary. Residual risks are those that occur after the application of the mitigation measures that are assessed during EIAs. The outcome of these assessments is typically reviewed by the regulatory agencies to determine if they are acceptable or to see if the activity is likely to result in unacceptable impacts. If the residual impact is deemed unacceptable, a survey may not be permitted or additional mitigation measures may be required. Thus, at a minimum, the E&P industry must comply with the regulatory requirements. In the absence of regulatory requirements or when there is a need to go above and beyond the minimum requirements, the ALARP principle can be applied. This ALARP approach and inclusion of a risk-based element are currently insufficiently adopted in most guidelines for which often fixed sets of mitigation measures are proposed, independent of the potential impacts on marine mammal populations. Future guidelines and frameworks would benefit from applying a risk-based approach.

Recommendations for Future Studies and Research and Development

Because of concern over anthropogenic sound sources on marine mammal populations, the number of studies and research programs has increased over the past decades (Southall et al., 2007, 2019; Cato et al., 2013; Costa et al., 2016; NMFS, 2016, 2018; Harris et al., 2017; Jiménez-Arranz et al., 2017). These efforts have enhanced our understanding of marine sound sources, propagation pathways, and impacts on marine mammals, and have improved our ability to manage these impacts. However, numerous key data gaps remain due to the multidisciplinary and complex nature of this issue as well as an expansion in focus areas.

Whereas approximately 10 to 15 years ago the main concern was that airguns would result in mortality or injury to marine mammals, at present, this focus has expanded in three dimensions from the perspective of (1) the source – primarily airguns, but increasingly this also includes drilling, pile driving, and other geophysical equipment (MacGillivray et al., 2014; Austin et al., 2018); (2) the species groups – mainly marine mammals, but there is increased focus on fish, invertebrates, and even plankton (McCauley et al., 2017; Slabbekoorn et al., 2019); and (3) types of impacts – from mortality and injury to increased focus on disturbance and masking (Villegas-Amtmann et al., 2015, 2017; Costa et al., 2016; Erbe et al., 2016; McHuron et al., 2018). Although our understanding of impacts of marine sound on marine mammals has expanded significantly over the years, some of the remaining priority knowledge gaps are described in the following section. This is not a complete assessment of all knowledge gaps, and various stakeholders may have different views on priorities.

Source

Although some acoustic characterization studies of the full volume range of single airguns and airgun arrays output have been conducted (Tashmukhambetov et al., 2009), higher resolution characterization over the full spectrum of frequencies containing acoustic energy is needed to verify and, if needed, modify source models (Ainslie et al., 2016). Furthermore, a wider variety of SSV measurements of E&P sources would be useful, such as drilling rigs, subsea equipment, floating oil and gas processing facilities, and other geophysical equipment such as sparkers, boomers, and marine vibrators, to better assess impacts of such equipment on marine mammals. Additionally, development of alternative sound sources that could reduce impacts on marine life is valuable.

Pathway

If parameterized correctly, propagation models are quite good in predicting propagation over short to medium distances (up to several km). However, more long-range propagation modeling verification measurements in different environmental conditions are needed to determine the accuracy, and need to improve, acoustic modeling over long ranges (10 to 100 km). Additionally, parameterization studies of acoustic models in different environments are required to improve the accuracy of the available acoustic propagation models.

Receiver

Audiograms and TTS measurements for a wider range of species are needed to depend less on interpolation between species, including development of novel methodologies to derive these in low-frequency species (mysticetes). Despite the extensive effort on weighting curve development, metrics, and methods used for determination of injury thresholds, more effort is needed to further improve these weighting functions and injury thresholds, which should include metrics and methods that are easier to apply for assessment and mitigation of impacts of cumulative exposure. As cSELs are calculated over prolonged periods of time (e.g., 24 h), an enhanced understanding of the role of hearing recovery between pulses, or period of silence within activities, is needed when applying this metric for injury thresholds as recovery in periods of silence is currently not considered. Southall et al. (2007) first proposed the use of the 24-h intermittency period to reset the SEL accumulation. Since then, the use of shorter interval periods are being suggested that capture the periods with highest SELs (Finneran, 2015; Martin et al., 2019; Southall et al., 2019), but this has not been adopted in regulations yet (e.g., NMFS, 2018). The need for the application of hearing weighting functions in the assessment and mitigation of behavioral responses, disturbance, and masking has been recognized (Tougaard et al., 2015; Tougaard & Dähnle, 2017; Kastelein et al., 2019a), but additional experimental studies are needed to further mature this topic.

More controlled behavioral response studies using E&P sources on a range of different species would be beneficial to enhance our understanding of the severity of the responses, their duration, and the influence of other, non-disturbance-related aspects (e.g., context, behavioral state, etc.) on behavioral responses. The application of 3-D acoustic tags will be instrumental for detecting fine-scaled changes in movement patterns as well as associated exposure levels. Outcome of these studies can then be used to further improve PCoD models to understand the "so what?" aspect of behavioral responses—that is, which type of responses, under what conditions (seasonality, duration, context, etc.), have a biological significance at a population level. These models could also be applied to better understand the issue of cumulative or aggregate impacts of multiple activities occurring in the same area—either at the same time or within the same season (Costa et al., 2016; NAS, 2017).

Monitoring

The E&P industry would benefit from the development of autonomous monitoring technologies, such as autonomous operated camera-based aerial systems or PAM arrays, to monitor changes in abundance and distribution of marine mammal populations in remote locations. Similarly, improved autonomous monitoring technologies to detect the presence of marine mammals near E&P activities, both in normal and poor visibility conditions, would be very useful to gain greater insight on the impact of those activities on abundance, behavior, and distribution of marine mammals.

Mitigation

There are multiple efforts ongoing in the E&P industry to either modify the way airgun arrays are used or to develop new and alternative sources for exploration of hydrocarbon-bearing reservoirs with lower SLs, which are aimed at decreasing the likelihood of injury or disturbance of marine mammals such as the development of marine vibroseis technology (Jenkerson et al., 2018). Similarly, from a marine mammal perspective, the further modification of airgun arrays (and other acoustic sources) with less or no unnecessary medium and high frequencies (> 200 Hz) will be beneficial as it reduces the potential for impact to the medium- and high-frequency species groups. For those E&P activities that generate sound without a purpose, such as drilling, pile driving, and shipping, effective quieting technologies will be instrumental in reducing sound levels. Lastly, numerous mitigation measures are regularly applied during E&P activities, such as seismic surveys, but for some of those measures, the efficacy has not been assessed yet. This would be useful to ensure measures are indeed protective. Related to this is the need to enhance our ability to quantify impacts of E&P activities on marine mammal populations, if any. The concept of offsetting impacts on populations would benefit from being advanced as well. For example, in some cases, marine mammal populations may benefit more from conservation activities that are not related to E&P activities. In those instances, it may be more efficient from a conservation point of view to contribute towards the implementation of species-specific conservation activities instead of implementing an extensive monitoring and mitigation program.

Acknowledgments

The author thanks Louis Brzuzy (Shell) for a detailed review of the manuscript; Robert Gisiner (IAGC), Marije Siemensma (Marine Science & Communication), Roberto Racca (JASCO Applied Sciences), and Michael Macrander (Integral) for their useful comments; and Kathleen M. Dudzinski (Managing Editor of *Aquatic Mammals*) and two anonymous reviewers, whose advice and constructive comments improved this manuscript.

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